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THE JOURNAL OF GEOLOGY

July-August 1943

RADIOGENIC HEAT IN ROCKS

NORMAN B. KEEVIL
University of Toronto

ABSTRACT

Results of hundreds of new radioactivity determinations on rocks and minerals plotted on frequency-distribution curves lead to lower probable rates of heat production than were estimated previously. This may be due in part to nonrepresentative sampling, and the need for more abundant data is emphasized. For this purpose analyses for radium alone are not satisfactory.

A rapid means of obtaining the rate of heat production from a single measurement of the rate of emission of α-rays, developed in 1939, is described and applied.

Owing to similarity in the rates of α-ray emission and in the rates of production of heat of the thorium and uranium series at their normal abundance ratios in rocks, the rate of heat production from disintegrations in these series may be calculated by means of the single equation, $H^1 = 2.15a$ calories per gram per million years (Th/UI assumed to be 3.5, and a the observed rate of α-ray emission in alphas per milligram per hour). It also appears to be satisfactory to assume that the percentage of K_2O equals $2.5a$, so that the total heat production, H, equals $2.25a$ cal/gm/My.

INTRODUCTION

Radioactive disintegration produces heat, a fact which can be simply demonstrated by a calorimetric experiment or by calculation of the kinetic energy of the emitted particles. It has long been appreciated that radioactive elements in ordinary rocks produce quantities of heat significant in geothermal problems—for example, in that of estimating geothermal gradients. What we still lack is sufficient knowledge of the distribution of radioactivity within the earth to warrant precise calculation.

The number of rocks for which the contents of both the major parent-elements, uranium and thorium, are known is so small that no representative average for any rock type can be stated. The number of rocks for which an analysis of potassium also is available is still less; actually the solution is incomplete without analyses for all other radioactive elements independent of these series, but because of their slow rates of decay the disintegration of rubidium, neodymium, samarium, and lutecium contribute negligibly small quantities of heat.

The need for more abundant radioactivity data raised the question of whether the tedious procedure of separate determinations of radium, thorium, and potassium were necessary or whether a more rapid method could be developed. In this paper a satisfactory method of obtaining the rate of production of radiogenic heat from a single measurement is described and applied to several hundred rocks and minerals.

LIMITED VALUE OF SEPARATE RADIUM AND THORIUM ANALYSES

In the past a great many analyses of radium of varying degrees of reliability

have been made by observing the ionization from its gaseous decay product, radon. When critical selections of these data are made, only a little over one hundred analyses are available for all types of rocks. Furthermore, radium is only one of forty-seven naturally radioactive elements, all of which contribute something to the total production of radiogenic heat. However, since radium is a member of a chain of radioactive elements which starts with uranium (U^{238}) and ends with an isotope of lead (Pb^{206}), and since uranium and actino-uranium (U^{235}) are isotopes, an analysis of radium serves to determine any or all of thirty members of these series when radioactive equilibrium is attained. (Equilibrium is reached in a million years in the uranium series and in a still shorter time in the thorium series, so that radioactive equilibrium is established in all but Recent rocks.)

Confining one's analyses to radium leaves the problem only half-solved, since

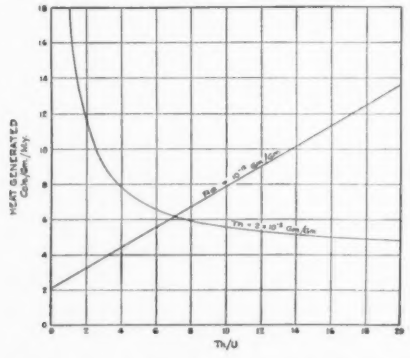

FIG. 1.—Errors introduced by variation in Th/UI in calculating H' from radium or thorium determinations alone (assuming $Th/UI = 3.5$).

the thorium and uranium series are about equally important in both geothermics and geochronology. The chief reason for the earlier concentration on radium was the relative ease with which quantities as small as 10^{-12} gm/gm could be determined. This limited study of terrestrial radioactivity appears, however, to be

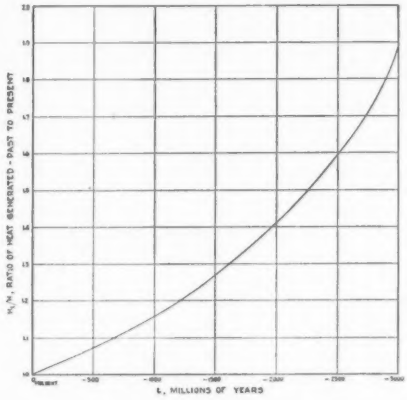

FIG. 2.—Curve for obtaining the heat, Ht, generated at any time in the past, t, from the present values of radiogenic heat, H.

continuing in spite of the development of simple methods of analysis of small quantities of thorium and of methods which are independent of standards.

Several direct analyses of thorium in rocks have been made by the thoron method,[1] and a few thorium contents calculated indirectly.[2] However, averages from these data cannot be representative enough for geothermal calculations.

So many determinations of radium have been made without corresponding

[1] W. D. Urry, "Determination of the Thorium Content of Rocks," *Jour. Chem. Phys.*, Vol. IV (1936), pp. 34–40; "Ages by the Helium Method," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1101–20; Vol. XLVII (1936), pp. 1217–34; N. B. Keevil, "The Application of the Helium Method to Granites," *Trans. Roy. Soc. Canada*, Vol. XXXII, sec. 4 (1938), pp. 123–50; "Thorium-Uranium Ratios of Rocks and Their Relation to Lead Ore Genesis," *Econ. Geol.*, Vol. XXXIII (1938), pp. 685–96.

[2] R. D. Evans and C. Goodman, "Radioactivity Measurements of Rocks," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 459–90.

analyses for thorium that it is well to examine the usefulness of such data in geothermics. To use either a radium or a thorium analysis by itself to calculate the rate of heat production, one must assume some value of the thorium-uranium ratio. Figure 1 shows the inaccuracy of calculating the heat on the basis of such an assumption in this case. If a value of

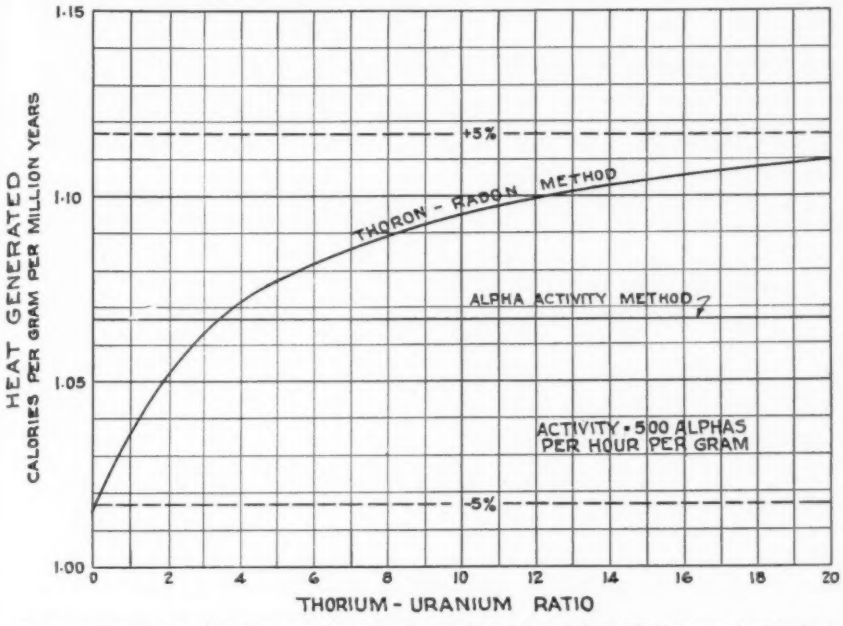

FIG. 3.—Comparison of the heat calculated by the alpha-activity method ($Th/UI = 3.5$) with the true heat production (thoron-radon method) over a wide range of thorium-uranium ratios.

Th/UI of 3.5, which is near the observed average value for rocks, is taken, a radium analysis on a rock whose actual Th/UI ratio is 20 would be three times too large, whereas an error of only 5 per cent would be introduced in the method used in Figure 3.

THORIUM-URANIUM RATIO

While the ratio of the thorium content to the uranium content varies from rock to rock, the ratio has seldom been found to approach 0 or to exceed 20. If one examines the distribution of values of Th/UI, one finds that most of the values fall within the limits Th/UI = 1 and Th/UI = 5, with a probable value slightly greater than 3. Thus, Arthur Holmes[3] reports an average of 2 on the basis of all reported data, Keevil[4] a value 3, and Evans and Goodman[5] a value 4, using selected data. Furthermore, A. O. Nier[6] has given independent mass spectrometric evidence for expecting a value close to 3.3. With these

[3] "The Origin of Primary Lead Ores," *Econ. Geol.*, Vol. XXXII (1937), pp. 763–82.

[4] "Thorium-Uranium Ratios . . . . ," *op. cit.*

[5] *Op. cit.*

[6] "Variations in the Relative Abundances of the Isotopes of Common Lead from Various Sources," *Jour. Amer. Chem. Soc.*, Vol. LX (1938), pp. 1571–76; and additional data (private communication).

facts it was shown[7] that an assumed value of Th/UI = 3.5 made unnecessary separate determinations of thorium or radium in age determinations of rocks of the earth's crust, irrespective of age. A single measurement of a, the rate of α-ray emission, is all that is required for the radioactivity factors in the age equation. This quantity is related to the concentration of uranium and thorium in the following way:

$$a = 0.368\text{UI} + 0.0886\text{Th}\ \alpha/\text{mg/hr}, \quad (1)$$

$$a = 1.04\text{Ra} + 0.0886\text{Th}\ \alpha/\text{mg/hr}, \quad (1a)$$

where the symbols UI and Th refer to concentrations of these elements in 10^{-6} gm/gm, Ra in 10^{-12} gm/gm.

The physical reason for the small error in making the assumption regarding Th/UI is the fact that the rate of production of α-rays (helium ions) is nearly the same in each of the series when thorium is 3.5 times as abundant as uranium, being in the ratio of 100 to 115.

THE ALPHA ACTIVITY METHOD

When it was realized three years ago that a single α-ray measurement sufficed for the radioactivity factor in the age equation,[8] it became obvious that the same measurement would provide a measure of the heat generated by radioactive disintegration within the rock, since α-rays are the chief source of radioactive heat. The ratio of heats generated by the two series is even closer to unity than in the timing mechanism, being 100 to 107. Accordingly, equations were developed for obtaining radiogenic heat directly from a single α-ray measurement; the validity of the method was tested with experimental data, and the feasibility of using an assumed value of the potassium-uranium ratio was pointed out.[9] Publication of these results has been delayed pending the accumulation of sufficient useful experimental data.

The values for the heat produced by naturally radioactive materials are those selected in 1939 for the "Handbook of Geophysical Constants."[10] The value for the uranium series has been corrected for a minor arithmetical error.

Uranium and actinouranium series	0.75 ± 0.03 cal/gm/yr
Thorium series	0.20 ± 0.01 cal/gm/yr
Potassium	$5 \pm 2 \times 10^{-6}$ cal/gm/yr

Therefore the heat production, H', due to the uranium and thorium series, is given by the radiogenic heat equation

$$H' = 0.75\text{UI} + 0.20\text{Th cal/mg/My} \quad (2)$$

It is clear from equations (1) and (2) that

$$H' = 2.15a \text{ cal/gm/My} \quad (3)$$

when Th/UI is 3.5.

In preparation for the experimental measurements, a finely ground sample is deposited on a metal disk from a suspension in alcohol. This deposit, of known weight and area, is exposed to the interior of a brass chamber, and a fraction of the emitted α-particles counted by means of suitable amplifying and recording systems. The fraction counted can be found experimentally or calculated theoretically. This measurement suffices for the determination of the concentrations of the three α-emitting series and their rates of heat production.

[7] Keevil, "The Calculation of Geological Age," *Amer. Jour. Sci.*, Vol. CCXXXVII (1939), pp. 195–214.

[8] *Ibid.*

[9] Keevil, unpublished manuscript (1939), limited distribution.

[10] Evans, Goodman, and Keevil, "Handbook of Physical Constants," sec. 18, "Radioactivity," *Geol. Soc. of Amer. Special Paper No. 36* (1942), pp. 267–77.

INCLUSION OF POTASSIUM IN HEAT EQUATION

Radioactive disintegration of the potassium isotope of mass 40 into calcium produces only a minute quantity of heat, but, owing to the abundance of potassium in rocks, this contribution is about one-tenth as important as either the uranium or thorium series. The radiogenic heat equation containing all significant terms is,

$$H = 0.75\mathrm{UI} + 0.20\mathrm{Th} + 0.05\mathrm{K} \ldots . \quad (4)$$

or

$$H = 0.75\mathrm{UI} + 0.20\mathrm{Th} + 0.041\mathrm{K_2O}, \quad (4a)$$

where K and K_2O are expressed in percentages and the symbols for the radioactive elements refer to parts per million, as before. It will be observed that the potassium content may vary over an appreciable range and still introduce an error of less than 20 per cent in a typical rock. Actually the variation in potassium relative to the radioactive elements does not appear to be great, and many investigators have noted a relationship between the uranium and potassium contents of rocks. This suggested the use of a constant for the potassium-uranium ratio. Taking a value

$$\frac{\mathrm{K}}{\mathrm{UI}} = 1.4 ,$$

based upon averages of rock analyses, and retaining the previous assumption of Th/UI = 3.5, the expression for radiogenic heat reduces to

$$H = 2.25a \text{ cal/gm/My} . \quad (5)$$

This simple equation serves to calculate the heat produced in most rocks merely from a single measurement of the α-ray activity.

RATE OF HEAT PRODUCTION IN THE PAST

To find the amount of radiogenic heat liberated in the sample at any time, t, in the past—such as the time of consolidation of the rock, one has only to correct the present contributions from the UI (0.72 cal/gm), AcU (0.46 cal/gm) and Th (0.20 cal/gm) series and from potassium (5×10^{-6} cal/gm) by means of the factor $e^{\lambda t}$, where λ is the approximate decay constant.[11] In a typical rock in which

[11] The values for the heats produced per gram are calculated from the α-ray energies of the uranium and thorium series, which are taken to be 89 per cent of the total disintegration energy. The disintegration of radium into radon and helium, for example, is accompanied by 5,000,000 electron volts or 2×10^{-13} cal., while the whole chain of disintegrations in the uranium series contributes 1.85×10^{-12} cal.; multiplying this figure by λUI and Avogadro's Number and dividing by the atomic weight, this amounts to 0.72 cal/yr/gm of UI. For potassium 40, which comprises 0.01 per cent of normal potassium, the heating effect is calculated from data on β- and γ-ray activities and energies. Heats generated per disintegration, h, are UI = 1.85×10^{-12} cal., AcU = 1.83×10^{-12} cal., Th = 1.54×10^{-12} cal., and K = 7×10^{-15} cal. The heat being generated at any time in the past H_t, may be calculated by summation of the terms $h\lambda Ne^{\lambda t}$ as follows:

$$\left.\begin{aligned} H = {} & \frac{(1.85 \times 10^{-12} \times 1.537 \times 10^{-10} \times 6.02 \times 10^{23} e^{0.154t}\,\mathrm{UI})}{238} \\ & + \frac{(1.83 \times 10^{-12} \times 9.83 \times 10^{-10} \times 6.020 \times 10^{23} e^{0.983t}\,\mathrm{AcU})}{235} \\ & + \frac{(1.54 \times 10^{-12} \times 4.99 \times 10^{-11} \times 6.02 \times 10^{23} e^{0.0499t}\,\mathrm{Th})}{232.12} \\ & + \frac{(7 \times 10^{-15} \times 4.33 \times 10^{-10} \times 6.02 \times 10^{23} \times 0.000109 e^{0.433t}\,\mathrm{K})}{39.1} \text{ cal/gm/yr} , \end{aligned}\right\} \quad (7)$$

which reduces to equation (4) when $t = 0$ and when UI and Th are expressed in units of 10^{-6} gm/gm and K in percentage to give calories per gram per million years. When Th/UI = 3.5 and K/UI = 1.4

Th/UI = 3.5 and K/U = 1.4 or K/a = 2.06, the ratio of the heat produced t years in the past, H_t, to that being generated at present, H, is found to be

$$\frac{H_t}{H} = \frac{1.06e^{0.154t} + 0.049e^{0.983t} + 1.03e^{0.05t} + 0.10e^{0.43t}}{2.25}. \qquad (6)$$

The change in this ratio with time is shown in Figure 2. This curve can be used to compute the rate at which radioactive heat was being produced at the time of crystallization.

LIMITS OF ERROR

While the major source of radioactive heat is in α-ray emission from the uranium and thorium series, the validity of making a single α-ray measurement as an index of the heat production must be tested. The chief variable is the thorium-uranium ratio, and Figure 3 shows that the error introduced in assuming a constant value of 3.5 is less than 5 per cent within a range of Th/UI ratios from 0 to 20, which more than covers the normal distribution in rocks. That a constant value can be used with such accuracy in spite of wide differences in actual concentrations is due to a fortunate similarity between the disintegration processes in the two series.

Precise determinations are theoretically possible by the thoron-radon method, but present experimental errors are greater than 5 per cent, and uncertainties due to the natural inhomogeneity of terrestrial materials are likewise appreciable. This permits the use of the simple and more rapid α-activity method in the study of most terrestrial materials. However, when the activity is low (less than 0.1), the radon-thoron method is to be preferred because of present experimental limitations and observational uncertainties at low counting rates. Because of the relatively small contribution of potassium, a greater margin of error is allowable in the value used for the heat from potassium 40 itself. The uncertainty in this factor—40 per cent—is, therefore, not overly serious, the effective probable error being less than 5 per cent in an average rock.

Since a potassium analysis is usually not available for rocks being studied for radioactivity, the problem is to ascertain the limits of error when a constant value of K/UI is assumed—for example, 1.4. Since we have shown Th/UI = 3.5 to be satisfactory, this amounts to the assumption that

$$\frac{K}{a} = 2.06 \qquad (7)$$

or

$$K_2O = 2.5a, \qquad (7a)$$

where K and K_2O are expressed in per cent, as before. This assumption is more satisfactory than taking a constant value of the potassium-uranium ratio because the errors due to variations in the Th/UI ratio are reduced to a maximum of 4.5 per cent. This is shown in Figure 4, where the limits of error in assuming K = 2 are shown by the intervals AB and BC. With an average activity of 1.0 α/mg/hr and uncertain Th/UI

(K/a = 2.06), equation (7) divided by equation (4) gives equation (6) (λUI = 1.537×10^{-10} yr^{-1}, λAcU = 9.83×10^{-10} yr^{-1}, λTh = 4.99×10^{-11} yr^{-1}, and λK = 4.33×10^{-10} yr^{-1}, UI = 139 AcU). Minor corrections in H since some of the curves in this paper were prepared do not affect the conclusions, as these are well within the probable error.

See also p. 478, ref. 2; and W. D. Urry, *Jour. Wash Acad. Sci.*, Vol. XXI (1941), p. 273.

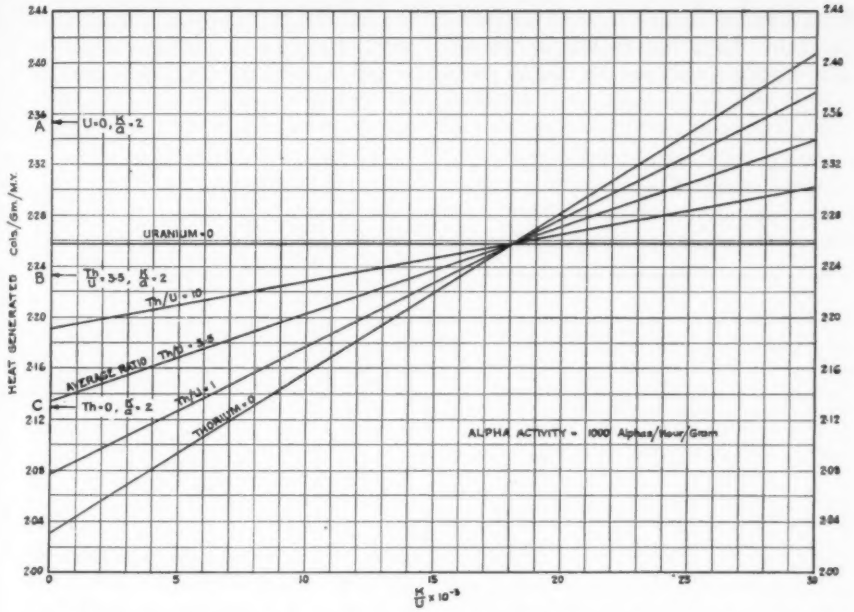

FIG. 4.—Variation in heat production with K/UI at different Th/UI ratios (concentrations in gm/gm). The maximum errors are less at $K/a = 2$ than at any assumed value of K/UI.

ratio, greater errors would enter if K were assumed to be proportional to UI or to Th (Fig. 5).

Not enough is known of the relative distribution of potassium and other radioactive elements to say whether or not one is justified in assuming a constant value of K/a over the whole range of activities. It is possible that many weakly α-active rocks may be relatively rich in potassium, in which case the heat production calculated from the α-activity alone would be low and subject to appreciable error.

The limits of error may be established from a consideration of the range of potassium contents of rocks. If one examines potassium analyses reported for all types of rocks, 0.08 gm/gm may be taken as a practical upper limit. As there is less than a 1 per cent chance that this value will be exceeded, 3.5 per cent may be taken as nearly the upper limit for basic

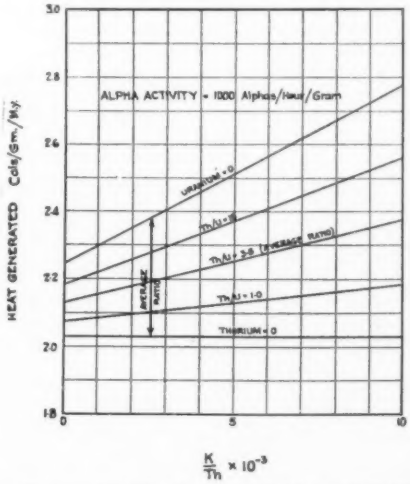

FIG. 5.—Variation in heat production with K/Th at different Th/UI ratios (concentrations in gm/gm).

rocks, a value which is close to the probable value for acidic rocks. The mean value for the potassium content of basic rocks is about 1 per cent.

In the present problem, then, the upper and lower limits of error may be estimated by taking K = 0.00 and 0.08 gm/gm and calculating the error introduced at any α-activity when K/a is assumed to

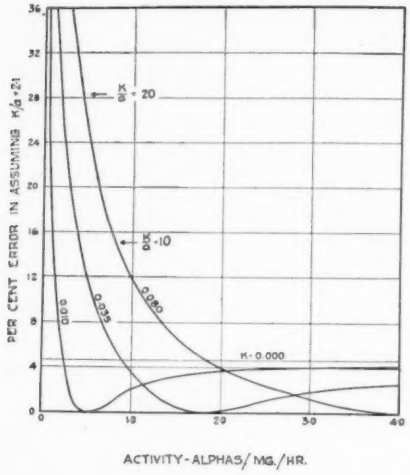

FIG. 6.—Error curves for several values of potassium content (0.08, 0.035, 0.010, and 0.000 gm/gm) over a range of alpha-activities. Curve 0.08 is nearly the upper limit for granitic rocks; curve 0.035 is close to the upper limit of concentration in basic rocks and represents a probable value for granitic rocks; curve 0.010 is representative of basaltic rocks.

be 2, using equations (4) and (5). For convenience, error curves for K = 0.01 and K = 0.035 are included in Figure 6.

It is shown in Figure 6 that the error in calculating H by means of equation (5) is less than 5 per cent whenever a exceeds 0.8; the probable error is greater than 15 per cent only when a is less than 0.4 for granitic rocks or less than 0.15 for basaltic-type rocks—and the error is this large only if K/U reaches 6.8 or K/a exceeds 10.

Further experimental work is needed to establish the range of these ratios in rocks. However, it is likely that in weakly active rocks the potassium content is less than 1 per cent; and, if this is true, the simple equation (5) can be applied whenever a is greater than 0.05. And when a is less than 0.05, the experimental error exceeds 20 per cent in direct α-counting technique. It is therefore recommended that separate radon, thoron, and potassium analyses be made when a is within the range 0.00–0.05, if more accurate thermal data are desired. This will be the case with many ultrabasic rocks and meteorites.

In calculating the heat produced by a rock at any period t in the past (Fig. 2), the error due to assumptions made in the present method becomes the larger the greater the value of t, as illustrated in the upper portion of Figure 7. This is due to the relatively greater heat-producing power of uranium and actino-uranium in the past, as shown in the lower half of the figure.

SUMMARY OF RADIOACTIVITY DATA

Relatively few reliable and complete determinations of the radioactive elements in rocks and meteorites have been made. Neglecting potassium, some determinations of activity (a = 0.104 Ra + 0886Th α/mg/hr) have been made by F. A. Paneth,[12] Holmes,[13] Urry,[14] Evans

[12] W. J. Arrol, R. B. Jacobi, and F. A. Paneth, "Meteorites and the Age of the Solar System," *Nature*, Vol. XIV, Part A (1942), pp. 235–38.

[13] Holmes and Paneth, "Helium Ratios of Rocks and Minerals from the Diamond Pipes of South Africa," *Proc. Roy. Soc. London*, Vol. CLIV, Part A (1936), pp. 385–412.

[14] "Ages by the Helium Method," *loc. cit.*, and R. D. Evans, C. Goodman, N. B. Keevil, A. C. Lane, and W. D. Urry, "Intercalibration and Comparison in Two Laboratories of Measurements Incident to the Determination of the Geological Ages of Rocks," *Phys. Rev.*, Vol. LV (1939), pp. 931–46.

and Goodman,[15] and the writer.[16] This preliminary work has been enough to show the need for quantity of data to obtain reliable values of the radioactivity and rates of heat production of rocks constituting the earth's crust and to provide some insight into the geothermics of the earth's interior. It is now clear that a single measurement made on a single specimen from a body cannot be expected to provide any more than an approximate order of magnitude of the radioactivity. Variations by as much as a factor of 2 or more are common in determinations on two portions of the same sample, and different portions of a batholith may possess a contrast in activity of more than 20. It is apparent that proper sampling is an important consideration and that averages based on a limited number of determinations may be subject to large error. One or two high values caused by local variations may displace the average in a positive direction, and this may account in part for the tendency for lower values to be recorded as new data accumulate. A dozen determinations of the activity of rocks from widely different localities cannot be expected to yield adequate information about either the activity of any one particular area or that of one class of rocks—for example, of the granitic crustal layer.

Accordingly, results for each group of rocks have been plotted on a distribution curve. This method of reporting the data possesses the advantages of giving, at a glance, the most probable value of the radioactive content indicated by the present state of our knowledge, and also of giving the range in radioactivity for specimens already investigated. For example, intermediate rocks have been found to range in activity from 0.0 to 3.5, the most probable value being 0.5, lower than the average value of 1.0 α/mg/hr.

[15] *Op. cit.*

[16] "The Application . . . . ," *loc. cit.*, and "Thorium-Uranium Ratios . . . . ," *loc. cit.*

GRANITIC ROCKS

The distribution of radioactivity in granitic rocks studied before 1942 is shown in Figure 8. The data are rounded off to the nearest 0.5 (α/mg/hr). Only the values from different localities are included, an average value being taken where several samples were analyzed from one or more closely spaced outcrops.

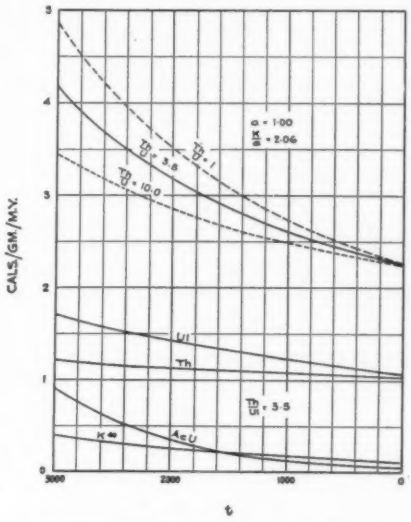

FIG. 7.—Variations in the rate of production of radiogenic heat with time in the past, t (present time, $t = 0$), for a sample of activity 1.00 alpha/mg/hr for different ratios of Th/U (assuming $K/\alpha = 2.06$). The contributions of the individual series are also shown for one value of Th/U.

In this and other curves the highest value on any ordinate represents the number of values found with that activity; for example, twenty-three granitic rocks were found to possess an activity between 0.75 and 1.25. Individual points along an ordinate are included so as to

indicate differences in sources of data. Granitic rocks were found to range in activity from 0.1 to 7.8, the average value being 1.47 α/mg/hr. However, the probable value is indicated by Figure 8 to be 0.94 α/mg/hr, corresponding to a present rate of heat production, H, of 2.21 cal/gm/My. While this figure is lower than averages reported previously, it cannot be considered representative, owing to the predominance of Canadian intrusives studied by the writer.

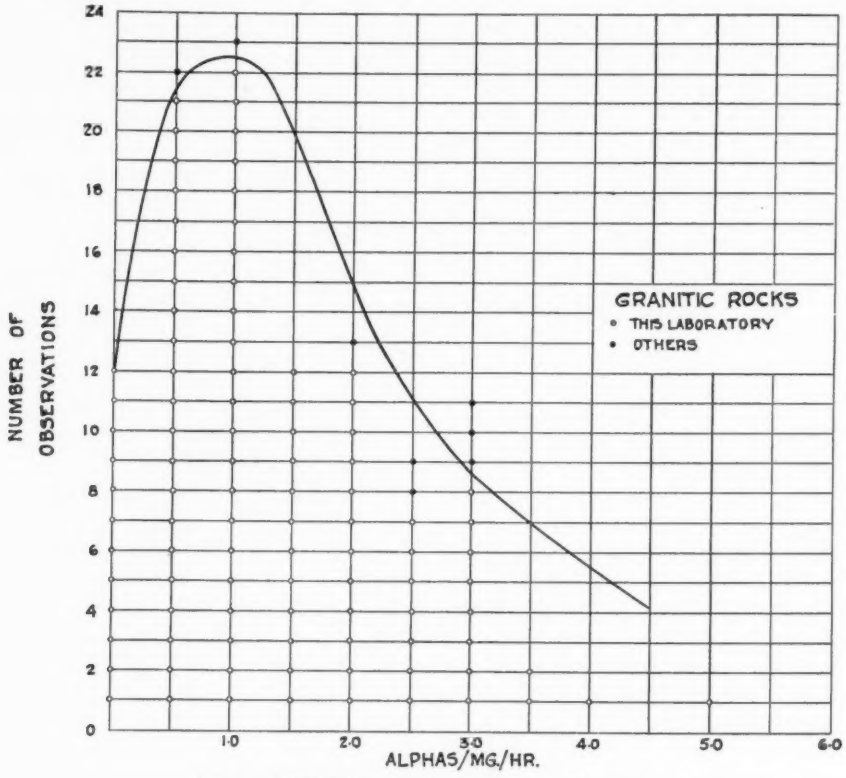

FIG. 8.—Distribution of radioactivity in granitic rocks

OTHER ACIDIC ROCKS

The distribution of acidic porphyries, syenites, pegmatites, and lavas, about half of which were collected in Canada, is shown in Figure 9. The activities range from 0.1 to 167, the average value (excluding the high value of 167) being 1.65 and the probable value about 0.5 α/mg/hr.

INTERMEDIATE ROCKS

The activities of intermediate rocks from over fifty localities range from 0.00 to 3.40, averaging 1.01 α/mg of sample per hour. A probable value of 0.55 α/mg/hr (Fig. 10) yields a probable value for the rate of heat production of 1.25 cal/gm/My in intermediate rocks from Canada and the western states.

BASALTIC AND OTHER BASIC ROCKS

Of a few hundred determinations of basic rocks by Urry (corrected values) and the writer, those of different age and locality are plotted in Figure 11. The activities range from 0.00 to 6.37, giving an average of 0.68 α/mg/hr. The probable value indicated by data obtained in this laboratory is 0.4; that including all data, 0.5 α/mg/hr. A value of 0.45 leads to a present rate of heat production of 1.0 cal/gm/My.

ULTRA-BASIC ROCKS

Fourteen different ultra-basic rocks showed activities varying from 0.00 to 0.82, the average being 0.053 α-rays emitted per hour from a milligram of sample. The distribution of the results

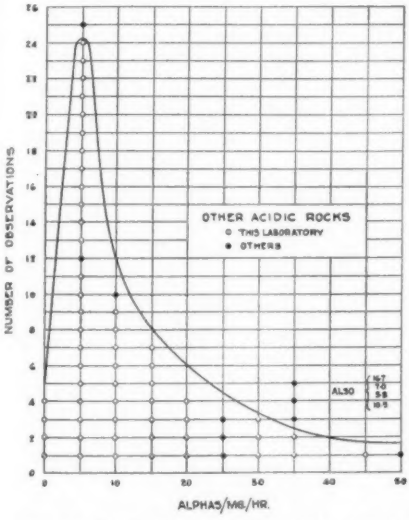

FIG. 9.—Distribution of radioactivity in acidic rocks other than granites.

suggests a rate of heat production between 0 and 0.1 cal/My for 1 gm of rock.

SEDIMENTARY ROCKS

A large number of determinations have been made on sedimentary rocks, many of these being short observations with relatively high probable error. However, several runs were usually made on the same rock, so that the over-all time of

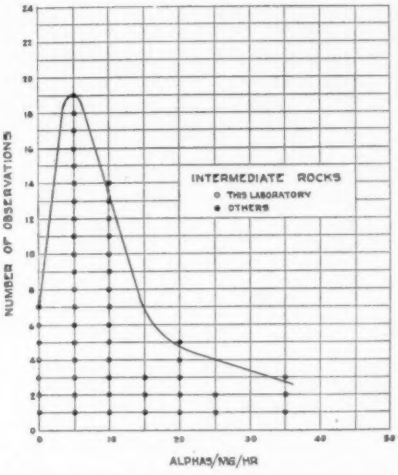

FIG. 10.—Distribution of radioactivity in intermediate-type rocks.

recording α-ray emissions was as large as normal runs (over 6 hours). The activities range from 0.00 to 8.2, the average value being 1.10 α/mg/hr. A probable activity of 0.7 yields a present rate of production of radiogenic heat of 1.7 cal/gm/My (Fig. 12).

SOILS AND UNCONSOLIDATED SEDIMENTS

Several hundred short-length recordings of α-ray emissions from soils, clays, and unconsolidated sediments have been made. Glacial clays and sands in Ontario ranged in activity from 0.70 to 5.1, averaging 1.97. Similar materials in central and eastern Alberta varied between 0.2 and 4.8, averaging 1.33 and a probable value of 1.25 (obtained from a frequency-distribution curve). Here the average of sand and clay was 1.20; of brown glacial clay, 1.25; and of blue clay, 1.45 α/mg/hr. Unconsolidated sediments from the

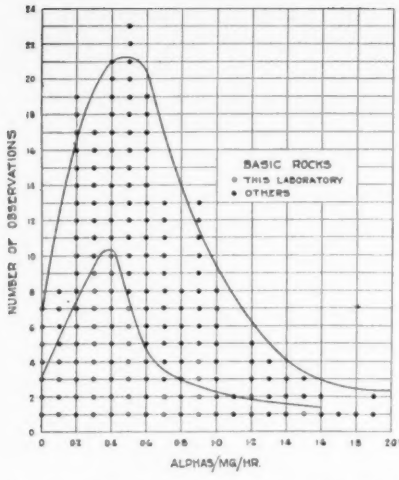

FIG. 11.—Distribution of radioactivity in basic rocks.

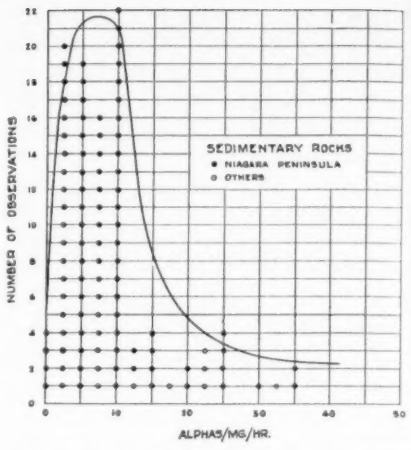

FIG. 12.—Distribution of radioactivity in sedimentary rocks.

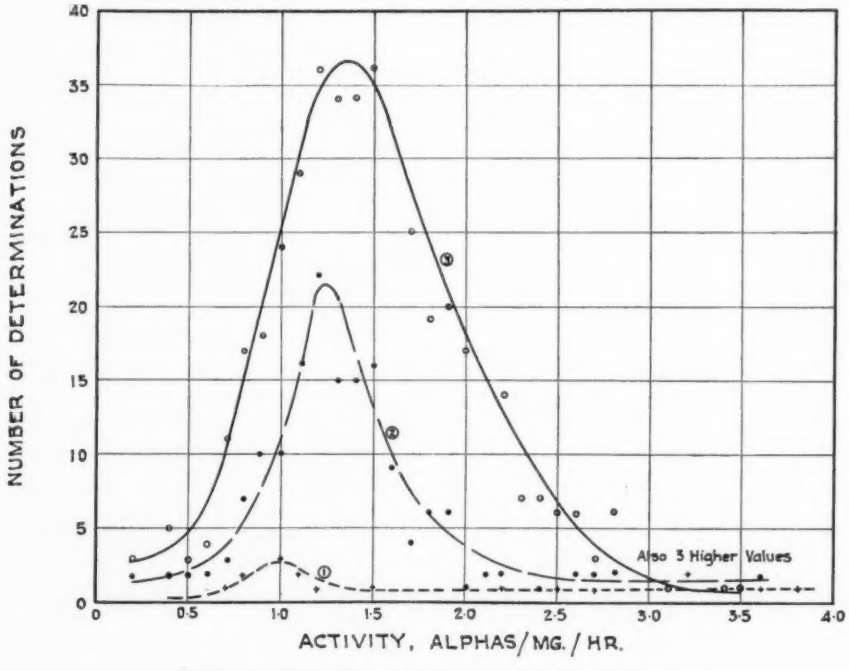

FIG. 13.—Distribution of radioactivity in soils and clays

Gulf Coast possessed activities in the range 0.4 to 5.25, averaging 1.61 and having a probable value of 1.4 α/mg/hr (Fig. 13). Here sand samples averaged 1.13; clay and sand samples, 1.25–1.50, depending upon the amount of clay; gray clay possessed an average activity of about 1.45; and red clay 1.48, although a number of mixed red with gray clay samples averaged 1.80 α/mg/hr.

RESULTS ON MINERALS

A number of ore minerals and minerals associated with or separated from rocks have been examined. Results for a number of these have been reported in a previous series of five papers. Data for the activity of "nonradioactive" minerals are summarized in Table 1. The probable values (fifth column) were estimated from distribution curves, the degree of accuracy of which can be judged from the number of specimens involved (fourth column).

TABLE 1

RESULTS FOR VARIOUS MINERALS

Mineral Group	Range in Activity*	Average Activity	Number of Determinations	Probable Value from Distribution Curves
Feldspar	0.01– 2.46	0.40	30	0.18
Pyroxene	0.03– 0.36	0.16	6	.....
Hornblende	0.02– 2.95	0.91	11	.....
Biotite	0.06– 2.74	0.70	8	.....
Other mafics†	0.02– 15.6	0.78‡	15	0.4
Other silicates§	0.00– 1.87	0.50	38	0.2
Quartz	0.00– 2.38	0.31	27	0–0.1
Magnetite	0.00– 13.8	0.75	14‡	0.1
Other oxides	0.00– 2.61	0.56	15	0.1
Sulphide‖	0.00– 0.99	0.24	19	0.25, 1.5‖
	1.03– 2.17	1.49	14	
Other minerals	0.10– 0.87	0.40	8	.....
Active silicates:				
Zircon	12.43–401.0	116.9	4	.....
Apatite	3.96– 56.2	.....	2	.....
Sphene	.....	266.0	1	.....

* Activity expressed in α/mg/hr.
† Mafics from ultra-basics lowest in activity.
‡ Two high values excluded.
§ Three high values excluded.
‖ Two groups.

RADIOGENIC HEAT IN ROCKS AND METEORITES

Although present data are too meager to warrant any precise use of radioactivity data in geothermal calculations, some general conclusions can be drawn. The usual order of activity of the rock types believed to be important components of the earth is confirmed as new data accumulate; this order is, in order of decreasing radioactivity: granitic, intermediate, basic, and ultra-basic rocks, stony meteorites, and iron meteorites. It is also becoming clear that the rates of production of radiogenic heat in rocks used in earlier geothermal theory have been excessive. In the computation of radioactivity data in the "Handbook of Geophysical Constants" the average values were roughly one-fourth of those used earlier by Holmes, and the more recent averages reported in Table 2 are lower still for granitic and ultra-basic rocks and for meteorites. Paneth's recent accurate radioactive studies of iron meteorites lead to an average value only 6 per cent of the previous estimate. Applying similar corrections to earlier data for stony meteorites, the average rate of

TABLE 2

APPROXIMATE RATES OF PRODUCTION OF RADIOGENIC HEAT IN ROCKS AS GIVEN BY PRESENT DATA

Type of Rock	Heat Production (Cal/Gm/My)			Per Cent Decrease of Average†
	Range of Values	Average Value	Probable Value*	
Granitic	0.2 –17.5	3.31	2.12	40
Intermediate	.0 – 7.7	2.27	1.25	.....
Basic	.0 –14	1.53	1.01	–10
Ultra-basic	.0 – 0.6	0.12	.....	85
Stony meteorites‡	.2 – 5	0.3	.....	20
Iron meteorites‡	0.005– 0.025	0.013	.....	85

* As obtained from frequency-distribution curves.
† Cf. Evans, Goodman, and Keevil, *op. cit.*, pp. 267–78.
‡ Calculated from Arrol, Jacobi, and Paneth, *op. cit.*, pp. 235–38, and Evans, Goodman, and Keevil, *op. cit.*, pp. 267–78.

heat production would be 0.27 cal/gm/My, a reduction of about 25 per cent.

More abundant recent data for rocks show little change in the average rates of production of radiogenic heat in basic and intermediate type rocks, but they indicate granitic and ultrabasic rocks to be definitely lower than previous estimates. This may be due in part, to nonrepresentative sampling of the granitic crust, but it may also be due to the inordinate effect of the inclusion of abnormally high values. The wide span in the activities of any one group of rocks has been noted previously; under such conditions the effect of values higher than average would tend to yield too high an average. This is well illustrated by plotting the data on distribution curves (Figs. 8–13). This procedure shows the fallacy of using averages of a dozen or so results and emphasizes the fact that *lower* values of the heat-producing power of rocks must be used in the future than are now in common use in geothermal calculation.

SUMMARY

Assuming a thorium-uranium ratio of 3.5, close to the average abundance ratio in rocks, the rate of heat production is given by $H = 2.15a + 0.05K$ cal/gm/My (where the activity, a, is expressed in α-rays emitted per gram per hour and K is the percentage of potassium by weight). Owing to the fact that radioactive disintegration of potassium normally accounts for only a small fraction of the heat produced, K/a may be assumed to be 2.06, so that $H = 2.25a$. On the basis of existing analytical data it is shown graphically that the errors in using this simple method are small enough to be neglected for present purposes.

Several hundred new results are combined with earlier data in frequency-distribution curves. The average value for granitic rocks is lower than recent estimates, which were in turn considerably lower than those used by Holmes. While this reduction may be due in part to the predominance of intrusives studied in Canada, some is due to the inclusion of nonrepresentative high values in early averages of meager data. This error may be eliminated in all cases by using a probable value indicated by distribution curves. When this is done, it is clear that radioactive heat values for all rocks must be lowered considerably from previous estimates.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge the assistance of A. R. Keevil and G. P. Crombie in assembling the experimental data. This research was made possible by a donation for geophysical research from the Viking Foundation.

THE GALISTEO FORMATION OF NORTH-CENTRAL NEW MEXICO

CHARLES E. STEARNS
Harvard University

ABSTRACT

The Galisteo formation consists of from 900 to at least 4,000 feet of sandstone, sand, and clay, variegated in color, together with minor amounts of conglomerate, fresh-water limestone, and water-laid tuff, deposited by rivers in a broad, deep inland basin. The Galisteo was succeeded without interruption by deposition of the Espinaso volcanics.

Fossil evidence indicates that the Galisteo formation is of Duchesnean (late Eocene or early Oligocene) age. At this time, north-central New Mexico had more rainfall than at present, but this may have been seasonal in nature. Forested highlands probably existed in the areas now occupied by the Sierra Nacimiento and the southern Sangre de Cristo Mountains. Large, perennial rivers flowed from the highland areas into and through the basin of deposition.

Upper Cretaceous rocks were deformed and eroded prior to deposition of the Galisteo formation. Further warping occurred during Duchesnean deposition, but this deformation may have followed different lines. The southern Sangre de Cristo Mountains may have been rejuvenated at this time. The igneous rocks of the Ortiz Mountains and the Cerrillos Hills intrude the Galisteo formation and the Espinaso volcanics. These formations were deformed and eroded before deposition of the late Tertiary Santa Fe formation. The Rio Grande depression was not outlined until late Tertiary time.

INTRODUCTION

The scanty fossil evidence here reported indicates that the Galisteo formation is of Duchesnean (late Eocene or early Oligocene) age. The formation thus has a more definite position in the early Tertiary sequence of New Mexico than has been heretofore assigned. Accordingly, the present restudy was undertaken and nearly completed. Because of uncertainty as to when the field work can be finished, it seems advisable to present the data already assembled. Presumably most of the conclusions here presented will be confirmed by later field work.

GEOGRAPHIC SETTING

Present outcrops of the Galisteo formation are confined to the Galisteo-Tonque area, between the south end of the Sangre de Cristo Mountains and the north end of the Sandia Mountains. The general relations of this area are shown in Figure 1.

Midway between the Sangre de Cristo and Sandia mountains is a north-south chain of hills, extending from the Cerros del Rio, west of Santa Fe, to South Mountain, northwest of the Estancia Valley. Within the Galisteo-Tonque area, and dominating it, the chain includes the Cerrillos Hills and the Ortiz Mountains. A broad, gravel-covered plain, drained principally by tributaries of Santa Fe Creek, slopes southwestward from the Sangre de Cristo Mountains to the Cerrillos Hills. Between the Cerrillos Hills and the Cerros del Rio, the plain merges with the basalt-capped Mesa Negra de la Bajada, through which Santa Fe Creek has cut a canyon 100–400 feet deep. The west edge of the Mesa Negra is the La Bajada escarpment, 300–500 feet high, overlooking the lowlands of the Santo Domingo Valley, in which Santa Fe Creek joins the Rio Grande.

Galisteo Creek enters the Galisteo-Tonque area at Lamy and flows southwest to the town of Galisteo. Here it turns and flows northwestward to the gap between the Cerrillos Hills and the Ortiz Mountains at the town of Los Cer-

rillos. Farther northwest, at Rosario Siding, it enters the Santo Domingo Valley, in which it joins the Rio Grande.

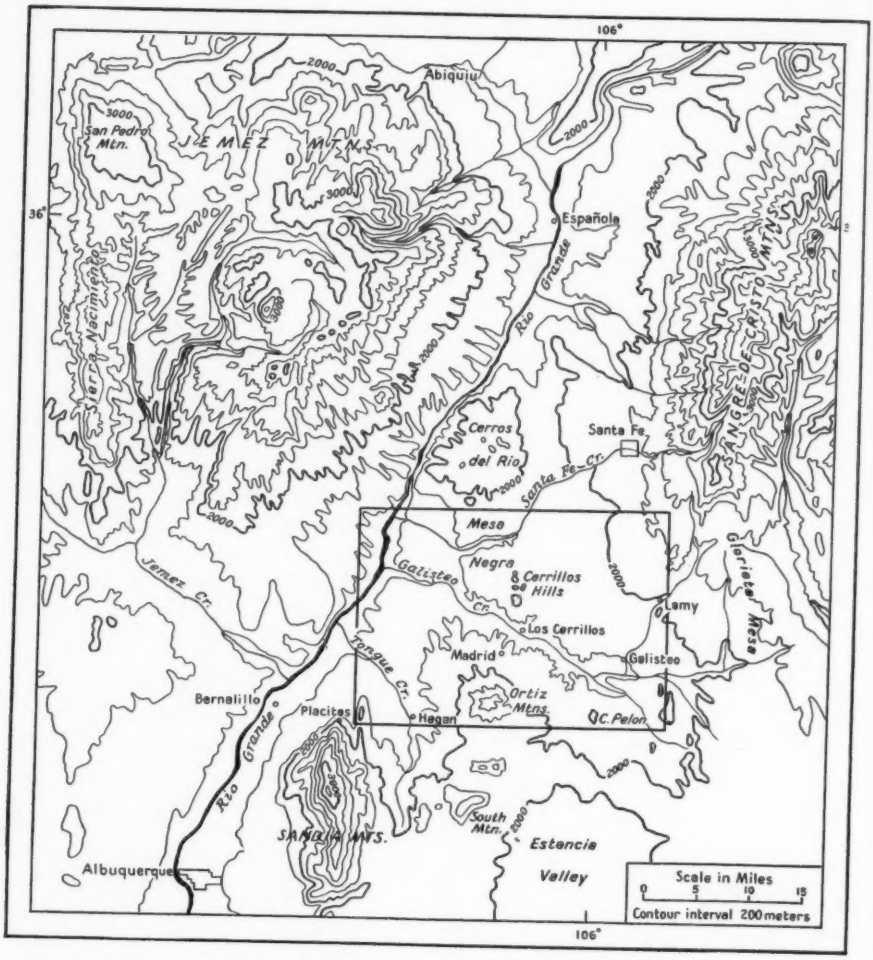

FIG. 1.—Index map of north-central New Mexico, showing location of the Galisteo-Tonque area. Redrawn from U.S. Geological Survey Base Map of New Mexico (Darton).

The town of Galisteo occupies the center of a broad lowland, the Galisteo Basin, excavated by Galisteo Creek and its tributaries. Glorieta Mesa forms the east boundary of the Galisteo Basin. An irregular escarpment rises about 100 feet to the gravel-capped plain in the north and northwest. South of Galisteo Creek, isolated Cerro Pelon forms the southwest boundary of the basin. To the south, an escarpment rises about 100 feet to the Estancia Valley.

Peripheral to the Ortiz Mountains is

the Ortiz pediment, an ancient, dissected erosion surface. Remnants of this surface are veneered with coarse, partially cemented gravel up to 125 feet thick. Over large areas bedrock is concealed by this gravel cap. East of the Ortiz Mountains, remnants extend nearly to Cerro Pelon. Gravel-capped remnants north of the Ortiz Mountains and bare spurs south of the Cerrillos Hills constrict the valley of Galisteo Creek at Los Cerrillos. By these bare spurs south of the Cerrillos Hills the Ortiz pediment merges with the Mesa Negra to the northwest and the gravel-covered plain to the northeast.

West of the Ortiz Mountains the Ortiz pediment and rough spurs extending northwest at lower elevations form a divide between the Santo Domingo Valley and the Tonque Valley, between the Ortiz and Sandia mountains. Most prominent of the spurs is the Espinaso Ridge, much of which is at the level of the Ortiz pediment. The Tonque Valley is an irregular lowland drained chiefly by Tonque Creek and its tributaries. The abandoned coal town of Hagan lies near the head of the Tonque Valley. Low spurs stretching northward from the Sandia Mountains separate the Tonque Valley from the Rio Grande Valley to the west.

PREVIOUS WORK

The Galisteo formation (Galisteo sand group) was named by F. V. Hayden[1] from exposures in the valley of Galisteo Creek, presumably those near Los Cerrillos. He recognized that the Upper Cretaceous coal measures were here overlain by a thick series of variegated sedimentary rocks, probably of early Tertiary age. He was impressed by the prominent sandstone beds of the Galisteo formation and gave the name "sandstone" (sand group) to it. Later workers have followed this usage. As hereafter shown, however, clay comprises about one-third of the formation, and other lithologic types occur. The term "Galisteo formation" is therefore used in this report.

D. W. Johnson,[2] in a study of the Cerrillos Hills, confirmed Hayden's observations. He estimated the thickness of the Galisteo formation to be 1,500 or 2,000 feet and noticed that it was overlain conformably by "trachytic" volcanics. He correlated plant remains from the coal measures at Madrid, identified by Knowlton, with the Fox Hills sandstone and suggested that the Galisteo formation might be of Laramie age. The intrusive rocks of the Cerrillos Hills were shown to be younger than the Galisteo formation.

W. T. Lee,[3] in a discussion of the Upper Cretaceous rocks in the vicinity of the Ortiz Mountains, paid some attention to the Galisteo formation and described two measured sections in the Tonque Valley. He also pointed out that some of the yellow sandstone near Los Cerrillos, included by Johnson in the Upper Cretaceous, belongs properly to the Galisteo formation.

Kirk Bryan and J. E. Upson,[4] in a study of the Santo Domingo Valley, describe the Galisteo formation in the northern end of the Tonque Valley. They separate the overlying andesitic(?) volcanics as a new formation, the Espi-

[1] "Preliminary Field Report of the United States Geological Survey of Colorado and New Mexico" (1869), pp. 66–68.

[2] "Geology of the Cerrillos Hills, New Mexico," *School of Mines Quarterly*, Vol. XXIV (1903), pp. 332–38.

[3] W. T. Lee and F. H. Knowlton, "Geology and Paleontology of Raton Mesa and Other Regions of Colorado and New Mexico," *U.S. Geol. Surv. Prof. Paper 101* (1917), pp. 198–217.

[4] "Geology and Geomorphology of the Santo Domingo Valley, New Mexico" (unpublished manuscript).

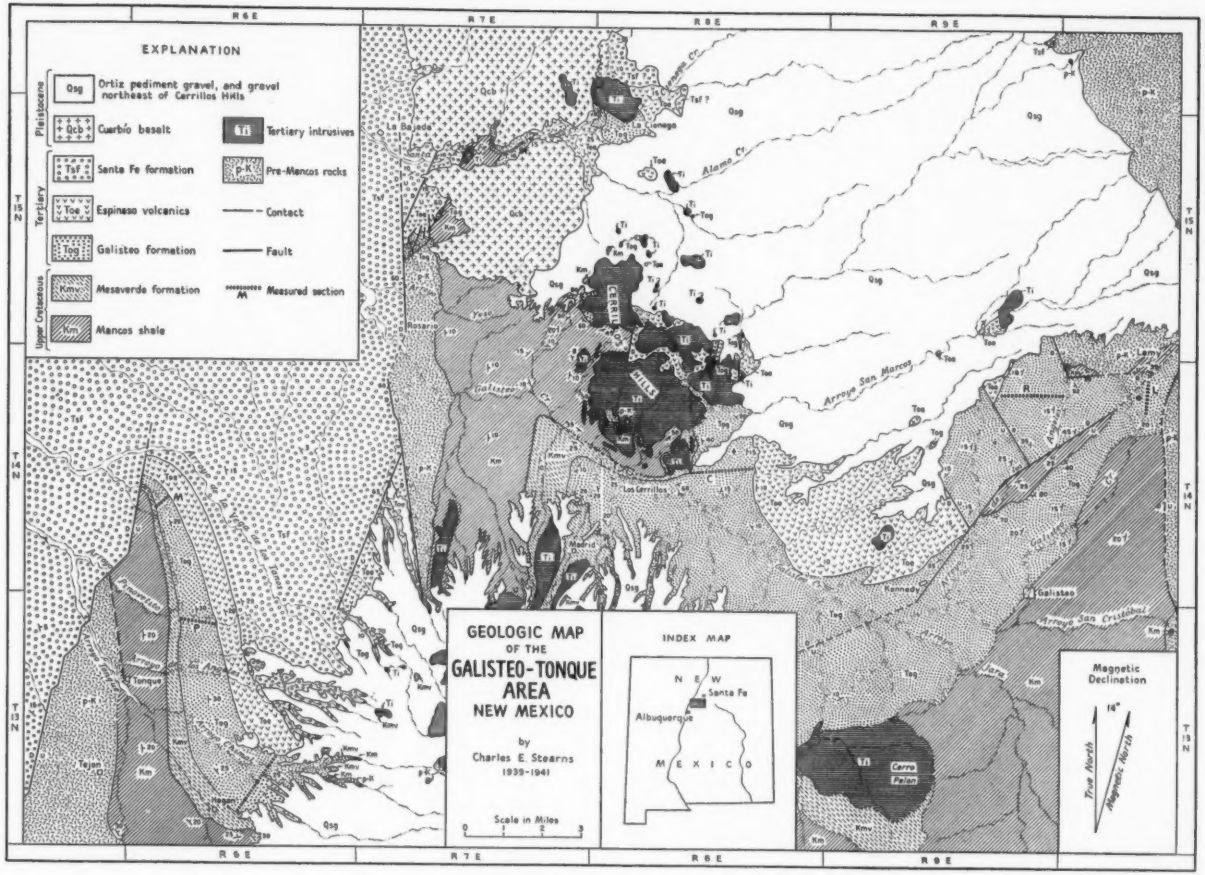

FIG. 2.—Geologic map of the Galisteo-Tonque area

naso volcanics, so named from the Espinaso Ridge, in which they are exposed.

AIMS AND METHOD OF PRESENT STUDY

The field work upon which this paper is based was carried on as part of a general areal study of the Galisteo-Tonque area. One of the problems investigated was the distribution, lithology, and general stratigraphic and structural relations of the Galisteo formation in this broad area. Field work was done during the summers of 1939, 1940, and 1941. It has been chiefly of a reconnaissance nature, supplemented by detailed study in favorable localities. Existing topographic maps are too generalized to serve as base maps. Aerial photographs, and drainage maps compiled from them on a scale of 1 inch to the mile, were therefore used. Stratigraphic sections were measured by pace-and-compass traverse. Petrographic and detailed stratigraphic studies have not been made.

DESCRIPTION

LITHOLOGY

The Galisteo formation is composed of fluviatile deposits, including sandstone, sand, conglomerate, clay, limestone, and water-laid tuff. Its distribution is shown in Figure 2.

Sandstone and sand.—The characteristic rock types of the formation are medium- to coarse-grained sandstone and sand. Together with lenticular pebbly sandstone and conglomerate, they comprise about two-thirds of the formation. Although grains of feldspar and of various crystalline rocks are present, almost all the sand grains are quartz. Most of the thicker beds are cross-bedded. The sand is in places unindurated, particularly in the upper part of the formation, but is in most places cemented by calcium carbonate to a soft, crumbly sandstone. Concretions are abundant. Limonite is present in many sandstone and sand beds as a stain, but it does not act as a cement. Most of the sandstone is gray-white or buff in color, but brightly colored yellow, brown, red, or pink beds are also common. Silicified wood is abundant in many sandstone beds.

Conglomerate.—Lenses of pebbly sandstone and fine conglomerate, commonly as channel fillings, are abundant in the sandstone beds. The pebbly sandstone contains well-rounded pebbles scattered in a matrix of clean sand (Fig. 3). Clay balls were observed in some localities. The fine conglomerate contains subangular to well-rounded pebbles crowded in a matrix of similar, but finer-grained, grit. In some localities channel fillings are heavily stained with limonite.

Diameters of pebbles in these lenses generally average between $\frac{1}{4}$ and $\frac{3}{4}$ inch. Pebbles as much as 6 or 8 inches in maximum diameter, however, are fairly common in pebbly sandstone beds of the upper part of the formation between Los Cerrillos and Lamy. The pebbles are chiefly of siliceous types—chert, chalcedony, quartz, quartzite, or rarely sandstone. Many have a high polish. In addition to siliceous types, granite, schist, gneiss, and porphyry can be found in some localities. Between Los Cerrillos and Lamy, pebbles of granite, gneiss, and schist are common in the upper part of the formation. Near La Cienega the top of the Galisteo formation carries pebbles of granite, sandstone, limestone, porphyry, and siliceous types in moderately arkosic sandstone. Occasional pebbles of porphyry are found throughout the formation but are common only in the upper hundred feet. At many localities pebbles of chalky rock, which may be ex-

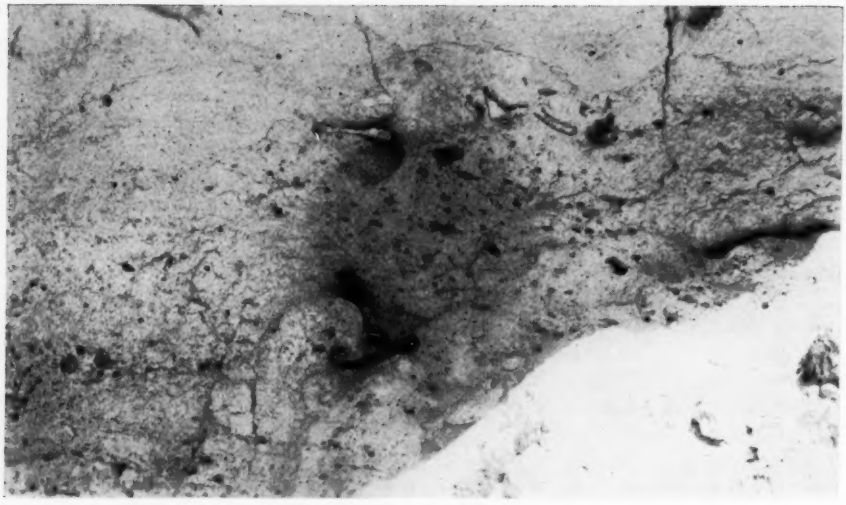

FIG. 3.—Pebbly sandstone of the Galisteo formation

FIG. 4.—Sandstone and clay of the Galisteo formation near Hagan

tremely decomposed porphyry, predominate in this range.

In striking contrast to the above types are a few beds of conglomerate. In the Tonque Valley there is a persistent horizon comprising two beds of coarse, massive conglomerate separated by 30 or 40 feet of sandstone. Locally, one conglomerate bed may be absent, but the horizon can be traced almost without break for 4 miles. The conglomerate contains well-rounded cobbles averaging 12–18 inches in maximum diameter, although maximum diameters of 3 feet were observed. Limestone, quartzite, granite, gneiss, and sandstone are the rock types, with limestone by far the most abundant. All the larger cobbles are limestone, and in many exposures it is the only rock type present. Many outcrops are heavily stained with limonite. A similar horizon of limestone conglomerate and sandstone, about 75 feet thick, occurs just east of Los Cerrillos (Fig. 5, Cerrillos section). West of Lamy, lenses of limestone conglomerate occur throughout nearly 1,000 feet of the formation (Fig. 5, Mosquero section). Most of the lenses contain pebbles about 6 inches in diameter, but two fairly persistent beds contain cobbles as much as 3 feet across. In all these localities limestone conglomerate occurs in about the same stratigraphic position, and it is probable that it represents a single horizon in the Galisteo formation.

Clay.—Variegated, unindurated clay makes up about one-third of the Galisteo formation (Fig. 4). It is generally highly colored—brick-red, maroon, purple, green, brown, or gray. Shaly bedding was observed in only a few localities. Thin lenses of sand occur in most clay beds, and the clay is commonly sandy. In many localities the clay is highly gypsiferous. In some localities calcareous nodules are abundant in clay. These vary from lumps an inch in diameter to flattish ellipsoidsal masses 2 feet across.

Limestone.—About 6 miles southwest of Lamy, two beds of fresh-water limestone, interbedded with red clay, occur in the zone which also contains limestone conglomerate. The beds are from 2 to 3 feet thick and consist of light-tan, nodular limestone. At another locality north of Kennedy a single bed of limestone 1 foot thick occurs at the top of the Galisteo formation. It is a massive, light-gray rock.

Water-laid tuff.—In a few localities thin beds of water-laid tuff or tuffaceous sandstone were observed. They are rare, however, except in the upper hundred feet of the formation. Here beds of massive gray or white tuffaceous sandstone are fairly common. A few beds of green tuffaceous clay were also observed.

The sandstone of the Galisteo formation is lithologically similar to that of the underlying Mesaverde formation. In many places, where sandstone beds of the two formations are in juxtaposition, an accurate determination of the Mesaverde-Galisteo contact is difficult or impossible. At other places, isolated outcrops occur which might be assigned to either formation. The following generally characteristic differences were used to distinguish the two formations:

1. Pebbly sandstone and fine conglomerate are abundant in the Galisteo formation but were not observed in the Mesaverde formation.
2. The fine-grained material of the Galisteo formation is clay, generally variegated; but the fine-grained material of the Mesaverde formation is consistently shale, generally tawny, gray, or black.
3. Silicified wood is characteristic of the Galisteo formation. At only one place, north of Madrid, carbonized plant remains heavily impregnated with quartz crystals were ob-

served in this formation. Carbonized plant remains and coal, to the exclusion of silicified wood, are characteristic of the Mesaverde formation.

4. Locally, pink, red, or yellow sandstone occurs in the Galisteo formation, but the sandstone of the Mesaverde formation is consistently gray-white or yellow-brown.

noted that the thickness obtained for the Pinovetito section differs markedly from the 4,750 feet obtained here by Lee.[5] The section was checked against the width of outcrop and attitude of beds and then remeasured: 2,100 feet seems to be the more correct figure for its thickness. The

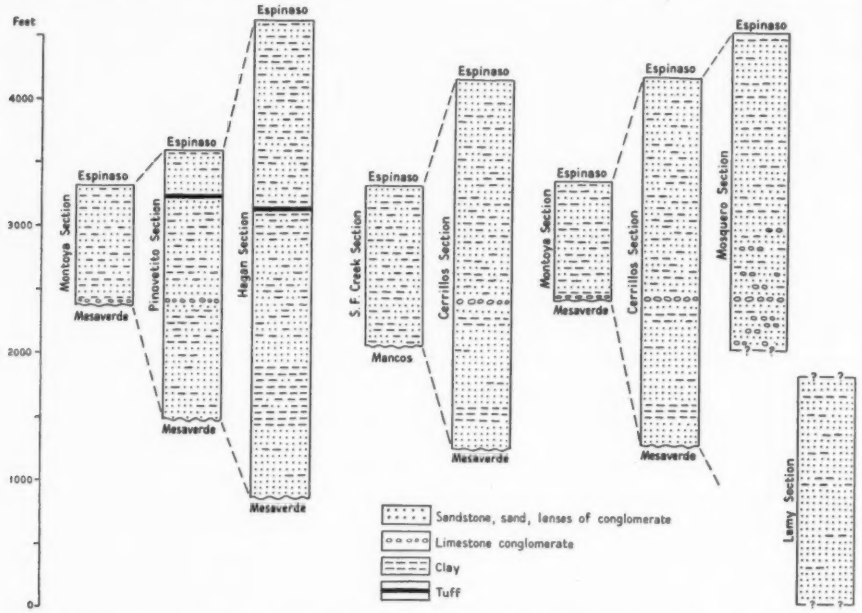

FIG. 5.—Columnar sections of the Galisteo formation. Montoya section measured at the north end of the Espinaso Ridge. Pinovetito section measured along the Arroyo Pinovetito. Hagan section measured north of Hagan. Santa Fe Creek section measured in the canyon of Santa Fe Creek in the Mesa Negra. Cerrillos section measured east of Los Cerrillos. Mosquero section measured west of Lamy, starting near the Ranchito Mosquero. Lamy section measured south of and on Cerro Colorado, near Lamy.

THICKNESS

Sections of the Galisteo formation were measured by pace-and-compass traverse at seven localities. Locations of the seven sections are shown in Figures 2 and 6. The data of the sections are summarized graphically in Figure 5. They are presented in three groups. The first group shows the variation in thickness along a nearly north-south line 7 miles long in the Tonque Valley. It should be second group of two sections shows the variation in thickness along a northwesterly line 10 miles across the Cerrillos Hills. The last group shows the variation in thickness between the Tonque Valley and Lamy, an east-west distance of 25 miles.

From the same data, an isopachous map of the Galisteo formation was prepared (Fig. 6). The variation in thick-

[5] Lee and Knowlton, *op. cit.*, p. 205.

ness indicated in the Tonque Valley is well supported by exposures along the strike. Projection of the isopachs from this area is based upon data from widely separated localities and is therefore subject to error. The Mosquero section of 2,500 feet and the Lamy section of 1,800 feet are both partial sections. The latter, a monotonous succession of yellow-brown sandstone and pebbly sandstone, does not, however, overlap the Mosquero section. Hence, although each section is incomplete, the original thickness of the Galisteo formation in this vicinity must have originally exceeded 4,000 feet by a considerable amount. The 4,000-foot isopach was drawn through the Mosquero section. If further data indicate that it should be changed, it would presumably be shifted to the west. This change would not affect the general isopachous pattern.

The thickness of the Galisteo formation varies from 900 to at least 4,300 feet. It increases systematically toward the southeast, where its maximum thickness probably exceeded 4,300 feet and may have been between 5,000 and 6,000 feet. The variation in thickness is not the result of post-Galisteo erosion, as the Espinaso volcanics follow the Galisteo formation without interruption. In the Montoya section, limestone conglomerate rests directly upon the Mesaverde formation. In the Pinovetito section, 4 miles to the south, the same horizon is 600 feet above the base of the Galisteo formation. The basin of deposition was therefore deeper in some portions than in others; and, as it filled, the area covered by sediments was enlarged. The systematic thickening of the Galisteo formation is not, however, the result of overlap upon an irregular topography (see below). The basin of deposition, therefore, must have been deepened and enlarged chiefly by contemporary warping.

ESPINASO VOLCANICS

The Galisteo formation is overlain conformably by more than 1,000 feet of andesitic(?) volcanics. Although their deposition followed that of the Galisteo formation without break, they are recognized as a separate formation—the Espinaso volcanics.[6] A description of this

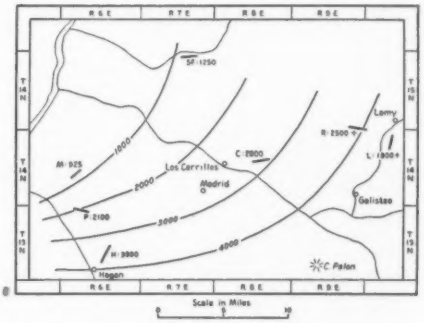

FIG. 6.—Isopachous map of the Galisteo formation in the Galisteo-Tonque area. Isopach interval, 1,000 feet. Locations of seven measured sections, and the thicknesses there obtained, also shown. *M*, Montoya section; *P*, Pinovetito section; *H*, Hagan section; *S F*, Santa Fe Creek section; *C*, Cerrillos section; *R*, Mosquero section; *L*, Lamy section.

formation is beyond the scope of this paper. It includes water-laid breccia, conglomerate, and tuff, with massive flows and explosive material in subordinate amount. Lithologic similarity suggests that the Espinaso volcanics are petrogenetically related to the intrusive rocks of the Ortiz Mountains and the Cerrillos Hills.

The contact between the Galisteo formation and the overlying Espinaso volcanics is transitional. The occasional pebbles of porphyry found throughout the Galisteo suggest that contemporary volcanism may have occurred in areas

[6] Bryan and Upson, *op. cit.*

outside the basin of deposition. The Espinaso volcanics, however, record a period of volcanic activity within this basin which terminated deposition of the Galisteo formation. In most places the uppermost hundred feet of the Galisteo formation contain abundant pebbles of porphyry and grade into fine-grained, water-laid tuff, forming the base of the Espinaso volcanics. In the Cerrillos section the Galisteo formation is succeeded with apparent abruptness by coarse, water-laid breccia. Lenses of yellow quartz sandstone about 10 feet thick, however, are interbedded with the first hundred feet of breccia.

FIG. 7.—Top of the Galisteo formation in the Arroyo Pinovetito. Green clay, to the right, is overlain by water-laid tuff of the Espinaso volcanics, to the left. Fossil bone occurs just below the prominent bed in the middle of the clay section.

FOSSIL CONTENT

Vertebrate fossils have been collected at two localities in the Galisteo formation, both of which are in the uppermost few hundred feet of the formation. During the summer of 1939 Dr. Theodore White, of Harvard University, made a small collection near Sweet's Ranch, east of Los Cerrillos. The material was taken from a sandstone probably less than 200 feet below the Espinaso volcanics, although its precise stratigraphic position is not known. In the collection Dr. White has identified *Teleodus* sp. and *Uintacyon* sp.

During the same summer a few vertebrate remains were obtained by the writer from tuffaceous clay in the zone of transition between the Galisteo formation and the Espinaso volcanics in the Pinovetito section (Fig. 7). Although this locality is stratigraphically higher than that from which White's collection was made, the two horizons represented are probably close in time of deposition. In the Arroyo Pinovetito (R. 6 E., T. 13 N., Sec. 4), abundant disarticulated bone is crowded in a bed of clay 1–2 feet thick and would probably repay more complete

excavation for vertebrate material. Dr. White examined that already collected and reports that "it contains a large and a small titanothere. The only horizon where this size range occurs is the Duchesne River of northeastern Utah."

As the material collected by Dr. White is compatible with such an age, it is concluded that the upper part of the Galisteo formation is of Duchesnean age.[7] This is considered by Wood and others to be uppermost Eocene but has also been called "lowermost Oligocene."[8] The distinction, which depends upon a definition of the Eocene-Oligocene boundary, is purely arbitrary. The Galisteo formation will therefore be called "Oligocene" in this paper as a matter of convenience. The age difference between the Galisteo fauna and the well-known Paleocene and early Eocene faunas of the San Juan Basin may thus be emphasized. As the Galisteo formation is of considerable thickness, its lower portion may include beds older than Duchesnean.

FIG. 8.—Silicified wood from the Galisteo formation east of Los Cerrillos

Silicified wood is abundant in many sandstone beds of the Galisteo formation, ranging from fragments a few inches long to great trunks 10 or more feet in length (Fig. 8). Many fragments carry a dull polish, as if water-worn. The abundance of large fragments, however, precludes the possibility that they were derived from older formations by erosion. The wood must have been carried into the basin of deposition in its original form and silicified only after it had come to rest.

[7] H. E. Wood *et al.*, "Nomenclature and Correlation of the North American Continental Tertiary," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 1–48.

[8] M. G. Wilmarth, "Lexicon of Geologic Names of the United States," *U.S. Geol. Surv. Bull. 896* (1938), Part I, p. 637.

Johnson[9] submitted specimens of silicified wood to Knowlton, who reported that they were of a dicotyledon, possibly *Quercus* sp. Bryan and Upson[10] made a small collection near the Montoya section, and collections were made by the writer at six other localities, most of them in the upper few hundred feet of the Galisteo formation. Dr. William C. Darrah, of Harvard University, kindly studied these seven collections. His report, in part, is as follows:

> Time has not permitted a full microscopic investigation of any of the species because of the slowness and cost of preparing thin-sections. Surface nitro-cellulose peels have been made from random samples (42).
>
> The bulk of the specimens belong to the conifers—the pine type, *Pityoxylon*. The species (one or several) is not named. The pine group has an extensive range in the higher altitudes of New Mexico, west Texas, and Arizona, down into southern Mexico.
>
> There are several genera of flowering plants —an oak, a *Fagus?* (beech), a woody legume related to *Acacia*, a diffuse-porous wood allied to poplar, and two indeterminate, ring-porous hardwoods.
>
> . . . . the plants are certainly of a moist, temperate, mixed-forest type of vegetation. The absence of palms, fern stems, and *Moraceae* distinguishes this series from the lowland Eocene sub-tropical and warm-temperate plant associations. In general, the plants represented by the Galisteo specimens resemble the southeastern American flora which, as indicated above, [also] ranges along the Rockies into Mexico.

ORIGIN AND CONDITIONS OF DEPOSITION

Terrestrial fossils, coarse grain, crossbedding, channeling, and lateral variation in lithology indicate that the Galisteo formation is an alluvial deposit. Pebbly sandstone and fine conglomerate were deposited in or near river channels, and clay was deposited on broad flood plains. The pebbles in pebbly lenses are generally well rounded and commonly highly polished. Rounding indicates transportation through some distance, and polish suggests that the rivers were highly silt-laden. Finer-grained material, however, was carried farther downstream or deposited on the flood plain during periods of overflow, as the pebbly sandstone is washed clean of it. These facts and inferences suggest streams of considerable volume with gradients sufficient to transport coarse material and with variation in flow so that large areas were flooded, and clays deposited, at high water.

Fresh-water limestone and calcareous concretions in clay indicate that temporary lakes formed upon the broad flood plains of the area. Furthermore, the rivers must have carried large quantities of material in solution. As the temporary lakes evaporated, some of this material was deposited as calcareous nodules and limestone. Some of the calcareous cement and limonitic stain now present in sandstone beds may have been derived in this manner. Much of the variegated clay is gypsiferous, suggesting that at times the flood-plain lakes were subject to extreme desiccation, which precipitated calcium sulphate. Extensive lake deposits, however, are conspicuously absent from the Galisteo formation. Presumably, therefore, the area was drained by a through-flowing, perennial stream system. It has been indicated above that the basin of deposition was affected by warping while it was being filled with sediment. Presumably the basin was formed, and deposition replaced erosion, through similar movements. Deformation, however, was at no time rapid enough to stop the drainage through and out of the Galisteo-Tonque area.

All of the pebbles in the Galisteo for-

[9] *Op. cit.* [10] *Op. cit.*

mation, except in the limestone conglomerate beds, are rock types resistant to chemical weathering. Fine-grained siliceous rocks, the most chemically resistant of all, are far more abundant than others. Although the chert pebbles were probably derived from the Magdalena limestone (see below), limestone pebbles are conspicuously absent. These facts, together with the generally nonarkosic nature of the sandstone beds, imply that the source areas of the Galisteo formation were subjected to intense chemical weathering. The red color of clays is sometimes ascribed to intense chemical weathering of source materials under warm, humid climatic conditions. This explanation of the red color of clays in the Galisteo formation is supported by the inference just made. Presumably, the colors of the variegated clays were produced by local variations in the conditions of weathering or by changes in the state of iron compounds produced after the clay reached a flood-plain environment.

CLIMATE

The present climate of north-central New Mexico is semiarid, with an annual rainfall of 10 inches in the lowlands and 15–30 inches in the mountains. The Galisteo flora contains large pines and hardwood, presumably derived from highland areas, which would require a fair amount of moisture. The presence of browsing titanotheres in the Galisteo drainage basin would also indicate a generous vegetation and therefore abundant moisture. These inferences and those made above of intense chemical weathering and perennial streams imply that the Oligocene climate was warm and humid. Rainfall must have been considerably greater than at present. It may, however, have been seasonal, with periods of comparative drought separating those of abundant rainfall. If gypsum was introduced into clay of the Galisteo formation by precipitation from flood-plain lakes, prolonged periods of desiccation, during which the flood plain was free from inundation, must have occurred. The polish carried by chert pebbles of the Galisteo may have been produced by abrasion in highly silt-laden streams but may also have been produced by abrasion of wind-borne dust during dry spells. Pine, the predominant member of the Galisteo flora, is well adapted to survive dry seasons.

Obviously, more evidence is needed before the Oligocene climate of north-central New Mexico can be defined. Rainfall was probably greater than that of the present; but its distribution, then as now, may have been seasonal.

SOURCE OF SEDIMENTS

Much of the quartz in the sandstone beds may have been derived from the Mesaverde formation, where it was exposed to erosion. However, the pebbles of chert, quartzite, granite, gneiss, and schist indicate that older rocks were also exposed in the drainage area. Some of the pebbles may have been re-worked from older sedimentary rocks, such as the Permian and Triassic "redbeds," but these are only locally conglomeratic and do not provide an adequate source for all the pebbles. Most of the chert was probably derived from the Pennsylvanian Magdalena limestone, the only older formation in near-by areas which contains abundant chert. One chert pebble collected from the Galisteo formation contains a tetracoral, identified by Dr. Willis P. Popenoe, of the California Institute of Technology. This chert pebble is certainly of Paleozoic age and presumably from the Magdalena limestone. The

pebbles of crystalline rocks were probably derived directly from pre-Cambrian rocks.

The streams which deposited the Galisteo formation therefore originated in areas where (1) the chert-bearing Magdalena limestone and (2) pre-Cambrian crystalline rocks were exposed. The rapid thinning of the Galisteo formation toward the northwest (Fig. 6) implies that one such area lay in that direction. Furthermore, the upper part of the Santa Fe Creek section is moderately arkosic. Pre-Cambrian rocks are now exposed in the Sierra Nacimiento, on the west side of the Jemez Mountains (Fig. 1). This great block was raised along a thrust fault in post-Wasatchian time.[11] F. S. Church and J. T. Hack[12] have shown that the structures produced during uplift are beveled by an extensive erosion surface of pre-Miocene age. In San Pedro Mountain, at the north end of the Sierra Nacimiento (Fig. 1), this erosion surface cuts across pre-Cambrian rocks. It is probable that part of this post-Wasatchian, pre-Miocene erosion contributed to the Galisteo formation. The Magdalena limestone, however, is atypical at the north end of the Sierra Nacimiento and was in large part removed by late Paleozoic erosion.[13] It is unlikely that the abundant chert pebbles of the Galisteo formation were derived entirely from this area.

Six-inch pebbles of granite, gneiss, and schist are fairly common in the upper part of the Galisteo between Los Cerrillos and Lamy but are rare in the Tonque Valley. Limestone conglomerate occurs through a wide range west of Lamy but is confined to one or two beds in the Tonque Valley. These facts suggest that some of the Oligocene drainage originated northeast of Lamy. In the Sangre de Cristo Mountains of northern New Mexico, sandstone predominates over limestone in the Magdalena "limestone."[14] In the southern part of this range, however, there are thick limestone beds with abundant chert nodules. Large areas of pre-Cambrian rock are also exposed and were exposed to erosion as early as the late Miocene.[15] This area provides a likely source for most of the chert and limestone pebbles of the Galisteo formation. If a highland area existed in the southern Sangre de Cristo Mountains during deposition of the Galisteo, the isopachs of Figure 3 must swing rapidly to the east and southeast within a short distance north of the Galisteo-Tonque area. There is no evidence that any highland existed at that time on the site of the present Sandia Mountains. In fact, extrapolation from Figure 3 would indicate that the basin of deposition extended over the area now occupied by these mountains.

During most of the period of deposition limestone was carried away, presumably in solution, and only the chemically resistant chert of the Magdalena limestone survived as stream pebbles. Coarse limestone conglomerate was deposited when erosion and transportation were rapid enough to preserve limestone from chemical decay. This condition obtained at only one time, when about two-

[11] B. C. Renick, "Geology and Ground-Water Resources of Western Sandoval County, New Mexico," *U.S. Geol. Surv. Water-Supply Paper 620* (1931), pp. 54–55.

[12] "An Exhumed Erosion Surface in the Jemez Mountains, New Mexico, *Jour. Geol.*, Vol. XLVII (1939), pp. 613–29.

[13] Renick, *op. cit.*, pp. 13–17.

[14] L. L. Ray and J. F. Smith, "Geology of the Moreno Valley, New Mexico," *Bull. Geol. Soc. Amer.*, Vol. LII (1941), pp. 183–86.

[15] C. S. Denny, "Santa Fe Formation in the Española Valley, New Mexico," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 688–91.

fifths of the Galisteo formation had been deposited. The abrupt appearance of limestone conglomerate in sections of the formation implies that the southern Sangre de Cristo Mountains, the probable source of the limestone cobbles, were suddenly elevated by diastrophic movement at this time. The equally abrupt disappearance of limestone conglomerate in most sections, however, is not readily explained. One would expect that the enhanced relief of the mountain area would decrease gradually and that limestone conglomerate or other coarse, massive conglomerates would continue to form during a considerable time interval. Such a succession of limestone conglomerate does occur west of Lamy but not in other localities. It may be, therefore, that the basin of deposition was also affected by diastrophism, so that erosion temporarily interrupted deposition in some places. The beds of limestone conglomerate now preserved may be only a much re-worked remnant of many such beds and may record a disconformity within the Galisteo formation in the western half of the Galisteo-Tonque area.

STRUCTURE AND RELATION TO OTHER ROCKS

PRE-GALISTEO UNCONFORMITY

Where exposed, the base of the Galisteo formation rests unconformably upon Upper Cretaceous rocks. The Upper Cretaceous rocks of the Galisteo-Tonque area include the Mancos shale, about 2,000 feet thick, and the Mesaverde formation, over 1,500 feet thick at Hagan, which contains productive coal seams. The unconformity between these rocks and the Galisteo formation is shown locally by channeling and by the gradual cutting-out of individual beds of the Upper Cretaceous. Although channels a few feet deep were observed, no evidence of much irregularity in the pre-Galisteo surface was found. It was presumably an erosion surface with low gradients.

The pre-Galisteo unconformity is shown regionally by variation in thickness of the Mesaverde formation. Sections of this formation were not measured, but its variation may be described in a general way. At Hagan and Madrid the Galisteo formation rests upon a few hundred feet of shale overlying productive coal measures. At the north end of the Espinaso Ridge, north of Madrid, and west of Cerro Pelon, the Galisteo directly overlies productive coal measures. The coal seams in these scattered localities are underlain by approximately equal thicknesses of sandstone, and it is probable that they represent roughly the same horizon in the Mesaverde formation. In the Galisteo Basin northeast of Cerro Pelon, and in the canyon of Santa Fe Creek in the Mesa Negra, the Galisteo rests upon the Mancos shale. In these areas the Mesaverde formation had been entirely removed by erosion. Using these rough observations, Figure 9 was prepared to illustrate the pre-Galisteo ero-

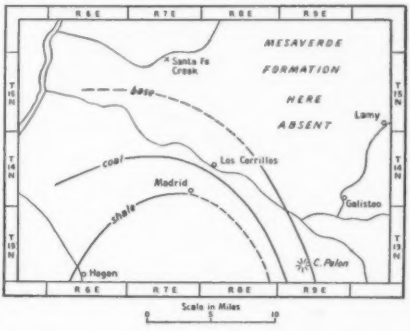

FIG. 9.—"Isopachous" map of the Mesaverde formation in the Galisteo-Tonque area, showing the amount of pre-Galisteo erosion.

sion of Upper Cretaceous rocks. "Isopachs" connect the localities where the Mesaverde formation is of about the same thickness, that is, the localities where pre-Galisteo erosion removed about the same amount of rock. One isopach (shale) connects those localities where the Galisteo formation overlies thick shale, which in turn overlies the coal measures, one (coal) those localities where the Galisteo formation overlies the coal measures, and one (base) delimits the area in which the Mesaverde formation has been entirely removed by pre-Galisteo erosion. The "isopach interval" is thus indefinite, and the map can be considered only an approximation.

Differential erosion of the Upper Cretaceous rocks in pre-Galisteo time amounted to at least 2,000 feet, as it exceeded the thickness of the Mesaverde formation (1,500+ feet at Hagan). This difference occurs within a few miles and is greater than would occur if an erosion surface of low gradient cut horizontal beds. The Upper Cretaceous rocks must have been deformed before erosion occurred. If the Mesaverde were originally of uniform thickness everywhere and if the pre-Galisteo erosion surface were a horizontal plane, Figure 9 would correspond in pattern to a structure-contour map of the deformation. Obviously, neither assumption can be supported, but it is probable that there is a general correspondence of pattern. Figure 9 probably roughly outlines part of a shallow basin produced in the Upper Cretaceous rocks in pre-Galisteo time. It has been indicated above that the variation in thickness of the Galisteo presumably resulted from broad warping during its deposition. The divergence of pattern between Figures 6 and 9 implies that deformation took place along different lines in the two periods, post-Cretaceous and early Oligocene.

POST-GALISTEO INTRUSIVES

The intrusive rocks of the Ortiz Mountains and the Cerrillos Hills are younger than the Galisteo formation and the Espinaso volcanics. Intrusive contacts are exposed east of the Cerrillos Hills and at La Cienega. Locally, these formations are altered in the vicinity of intrusive bodies. North and east of the Ortiz Mountains, sills related to the main intrusives of the mountains occur in the Galisteo formation. Dikes and sills, not shown in Figure 2, of rock types similar to the intrusives occur in the Galisteo formation and Espinaso volcanics throughout the area mapped. Many of the dikes are grouped radially to the Ortiz Mountains or to the Cerrillos Hills.

The forceful intrusion of stocks, laccoliths, and sills in these hills produced complicated local deformation of the invaded rocks. Most of the structures indicated by the complicated outcrop patterns (Fig. 2) in these areas, as well as others too small to be shown on a map of this scale, are the product of forceful intrusion. East of Los Cerrillos, beds of the Galisteo stand vertically (Fig. 10) as a result of near-by intrusive action.

As the Galisteo formation contains fossils of early Oligocene age, the intrusive rocks of the Ortiz Mountains and the Cerrillos Hills cannot be older than Oligocene. Lithologic similarity suggests that the Espinaso volcanics and the younger intrusive rocks are petrogenetically related. The intrusives, therefore, may have been emplaced soon after deposition of the Espinaso volcanics. They are probably of middle or late Oligocene age.

PRE–SANTA FE UNCONFORMITY

The Espinaso volcanics are overlain unconformably by the late Miocene and Pliocene Santa Fe formation. Where the unconformity is exposed, in the Tonque

Valley and about the Mesa Negra, the base of the Santa Fe formation consists in part of water-laid tuff, perhaps equivalent to the Abiquiu tuff of the Abiquiu quadrangle.[16] In most places angular unconformity cannot be demonstrated. Three miles northeast of Hagan, however, gulches cutting through the Ortiz pediment gravels partially expose (Fig. 2) the Santa Fe, apparently cutting across the east limb of a syncline in the early Tertiary rocks exposed to the south. The citas, see Fig. 1) the Sante Fe formation overlies the Mesaverde with angular unconformity. The early Tertiary and older rocks were therefore deformed and eroded in pre–Santa Fe time. The nature of the deformation cannot be inferred from present data.

GENERAL STRUCTURE

The present structure of the bedrock in the Galisteo-Tonque area was completed in post–Santa Fe time by the nor-

FIG. 10.—Vertical beds of the Galisteo formation east of Los Cerrillos. Beds to the left are overlain by horizontal pediment gravel.

syncline is broken by a fault which may not affect the Sante Fe formation. The base of the Santa Fe, unfortunately, is concealed by pediment gravel. Along the west base of the Sangre de Cristo Mountains, south of Santa Fe, the Sante Fe formation rests unconformably on pre-Cambrian granite-gneiss. The gravel-covered plain between these mountains and the Cerrillos Hills must be underlain in part by the Santa Fe formation. Its relation to the early Tertiary rocks of the Galisteo Basin is not exposed. At the north end of the Sandia Mountains (Plamal faulting which outlined the Rio Grande depression.[17] A normal fault of large displacement separates the Tonque Valley from the Rio Grande Valley to the west. Another normal fault with downthrow to the west, the Rosario fault, forms the eastern boundary of the Santo Domingo Valley. Although this fault can be traced only 6 miles south of Galisteo Creek (Fig. 2), it probably continues, with change of strike, underneath the pediment gravel flanking the Ortiz

[16] H. T. U. Smith, "Tertiary Geology of the Abiquiu Quadrangle, Rio Arriba County, New Mexico," *Jour. Geol.*, Vol. XLVI (1938), pp. 944–52.

[17] Bryan, "Geology and Ground-Water Conditions of the Rio Grande Depression in Colorado and New Mexico," *Regional Planning, Part VI: Rio Grande Joint Investigation in the Upper Rio Grande Basin* (Washington: National Resources Committee, 1938), Vol. I, Part II, sec. 1, pp. 209–15.

Mountains. The Rosario fault divides the Galisteo-Tonque area into two unequal blocks. The block west of the fault comprises a large syncline, the axis of which passes near Hagan, plunging northward underneath the Santa Fe formation in the Santo Domingo Valley. Locally, it is modified by subsidiary folds and faults. East of the Rosario fault is another broad syncline, between the Ortiz Mountains and Glorieta Mesa. A fault separates this syncline from the older rocks of Glorieta Mesa. The syncline is broken by another large fault, incompletely known, extending southwest from Lamy toward the Ortiz Mountains. It does not appear to be related to the faults of the Rio Grande depression. Other faults and folds, including those associated with intrusive rocks, further modify the broad syncline. North of Galisteo Creek the syncline passes underneath a thick gravel cover.

Since the Rio Grande depression was outlined by normal faulting, erosion has been the principal agent in modeling the present topography of the Galisteo-Tonque area. Streams graded to the Rio Grande first produced the Ortiz pediment, which bevels all but the most resistant rocks. Thus the Galisteo formation, which structurally belongs to the uplifted, highland blocks, is everywhere reduced to form part of the topographic lowlands. After completion of the Ortiz pediment, basalt flows from local centers of eruption covered the area of the Mesa Negra. Some of the gravel covering the plain east of the Mesa Negra was deposited at this time by streams whose courses were blocked by the basalt flows. Two pediments younger and less extensive than the Ortiz pediment have been recognized in the Galisteo-Tonque area. Gravel from 1 to 20 feet thick (not shown in Fig. 2) mantles these pediments over most of their area. A fourth erosion cycle is now in progress. Quaternary gravel, sand, and basalt deposited during these several cycles of erosion overlie the older rocks with strong angular unconformity.

CORRELATION

The Duchesnean fossils obtained from the Galisteo formation are, so far as is known, the first Oligocene fossils reported from New Mexico. Correlation on paleontologic evidence, if their assignment be correct, is limited to the Duchesne River formation of northeastern Utah and the lower part of the Sespe formation of California.[18] Eocene and "early Tertiary" formations have been described in several parts of New Mexico, and some of them will probably prove eventually to be contemporary to the Galisteo formation, but our present information is insufficient to suggest any definite correlations.

J. E. Upson[19] has recently pointed out the general proximity of many of the early Tertiary deposits of northern New Mexico and southern Colorado to the Rio Grande depression. He suggests that they may have been deposited in more or less related basins, the pattern of which was similar to that of the Rio Grande depression. Undoubtedly, these scattered deposits will eventually fit into systems of contemporary, more or less related basins. The inferences made above concerning the paleogeography of the basin in which the Galisteo formation was deposited are neither complete nor conclusive. They suffice to show, however, that this basin, at least, was unrelated to the Rio Grande depression, either as outlined in the late Tertiary or as it appears

[18] Wood *et al.*, *op. cit.*, Pl. 1 and p. 10.

[19] "The Vallejo Formation: New Early Tertiary Red-Beds in Southern Colorado," *Amer. Jour. Sci.*, Vol. CCXXXIX (1941), pp. 577–89.

at present. It is therefore believed more probable that the Rio Grande depression was not initiated until late Tertiary time. The early Tertiary basins, when their relationships are better known, will probably prove to belong to systems independent of the younger Rio Grande depression.

SUMMARY

In that part of north-central New Mexico just south of the eastern prong of the southern Rocky Mountains, deposition of the Mesaverde formation was followed by a period of mild deformation. Then ensued a period of erosion, during which an extensive surface of low relief was produced. Probably in the late Eocene, warping along new lines initiated a broad basin in the Galisteo-Tonque and adjacent areas. Streams fed by generous rainfall in the forested Nacimiento Uplift and southern Sangre de Cristo Mountains swept detritus into this basin. The basin was progressively deepened and enlarged during the late Eocene and early Oligocene, and the southern Sangre de Cristo Mountains may have been rejuvenated at one time during this period of deposition. In the basin, however, deposition kept pace with subsidence, and a through drainage was maintained. Finally, volcanic activity created new highlands and disrupted the former drainage. The period of volcanism was concluded by the emplacement of shallow-seated intrusive bodies, which greatly deformed the basin deposits into which they rose.

In late Tertiary time part of the area occupied by the early Tertiary basin of deposition contributed to a new system of basins, in which the Santa Fe formation was deposited. At the end of the Pliocene, normal faulting outlined another system of highlands and basins, integrated by the present Rio Grande and modeled by its tributaries. Present outcrops of the Galisteo formation are a small remnant of the original deposit preserved from erosion by favorable structure, while over large areas the formation is concealed by younger rocks.

ACKNOWLEDGMENTS.—The project of which this study is part has been under the direction of Professor Kirk Bryan, of Harvard University. It is a pleasure to acknowledge his constant interest, invaluable advice, and stimulating criticism, both in the field and during the preparation of manuscript. The writer was ably assisted in the field by Alwyn F. Marston, of Tufts College, in 1939; by James K. Grunig, of Harvard College, in 1940; and by Nathan O. Parker, of Tufts College, in 1941. Aerial photographs and drainage maps were furnished through the kindness of Mr. Kippe, of the Rio Grande District Office of the United States Soil Conservation Service at Albuquerque. Dr. Theodore White, of Harvard University, identified the vertebrate fossils collected and supplied information on those in his own collection. Dr. William C. Darrah, of the same institution, studied silicified wood in thin section. Dr. Willis P. Popenoe, of the California Institute of Technology, identified a tetracoral. The friendly interest and co-operation of many residents of the area, especially the Seligman family of Bernalillo, Mr. Benjamin Cano of Hagan, the Moores of Los Cerrillos, and Mrs. J. C. Underwood of Underwood Ranch, contributed largely to the progress of field work.

BIRD'S-EYE COAL FROM GREYMOUTH, NEW ZEALAND

M. GAGE
New Zealand Geological Survey
AND
J. A. BARTRUM
Auckland University College

ABSTRACT

Excellent examples of bird's-eye coal from the Tertiary bituminous coal measures of Greymouth, New Zealand, are described. The "eyes" consist of concentric rings, each ring a miniature ridge with slopes directed radially in opposite directions from the crest line of the ridge. They are believed to be the product of conoidal shearing induced in material of suitable physical character by tectonic stresses.

INTRODUCTION

One of the authors of this paper has studied the eye structures described herein during visits to the mines of the Greymouth coal field, New Zealand; the other (J. A. B.) is greatly indebted to Mr. Henry Loeb, of Canterbury University College, for bringing the occurrence of the structures to his attention. Both he and Mr. J. B. Leitch, of Greymouth, most kindly have furnished splendid series of specimens for study.

Professor D. J. Fisher, of the University of Chicago, drew the attention of the writers to the description and discussion of bird's-eye coal by R. Potonié,[1] but unfortunately his book is not procurable in New Zealand. Professor W. N. Benson, of Otago University, was so good as to inform the writers of an account of such coal in O. Stutzer and A. C. Noé's *Geology of Coal* and to lend them the volume.[2] E. S. Moore makes brief mention of bird's-eye coal in the second edition of his book *Coal*.[3] Apart from these two references, the authors have been unable to consult any literature bearing upon eye structures and must apologize for this shortcoming in their paper.

DESCRIPTION OF EYE COAL FROM GREYMOUTH

Perfect development of the "eyes" has been noted in only one mine of the Greymouth coal field, namely, that of Boote and Party, although somewhat similar structures, possibly related genetically to the others, are occasionally found in the coals of other mines of the field. In Boote and Party's mine there is eye structure in abundance in a finely laminated, fairly bright bituminous early Tertiary coal belonging to the Paparoa beds, which are the basal members of the Tertiary succession of the region.[4] Structures which at first sight appear similar in character have been recorded from brown coal of the Waikato coal field in the North Island of New Zealand by J. A. Bartrum,[5] but they differ from "eyes" in the smallness and uniformity of their size and in the closeness of their grouping both

[1] *Einfürhung in die allgemeine Kohlenpetrographie* (Berlin, 1924), pp. 53–61.

[2] *Geology of Coal* (Chicago: University of Chicago Press, 1940), pp. 249–53.

[3] (New York, 1940), p. 9.

[4] P. G. Morgan, "Geology and Mineral Resources of the Greymouth Subdivision," *N.Z. Geol. Surv. Bull. 13* (1911).

[5] "Cone-in-Cone and Other Structures in New Zealand Coals," *N.Z. Jour. Sci. and Tech.*, Vol. XXII (1941), pp. 209*B*–215*B*.

horizontally and vertically. Bartrum has suggested that they represent pit and mound structures.

In a perfect example the "eyes" are composed of concentric circular rings, the outermost ranging in diameter from less than $\frac{1}{3}$ inch to as much as 1 foot in the largest specimen observed. The larger examples invariably occur on pronounced fracture planes following the cleat (Fig. 1). In general, each individual ring is a miniature ridge due to the reversal of direction of slope at its crest of alternate, gently inclined concentric fractures: on one side of the crest the fracture surface slopes radially inward; on the other, outward. This reversal is not universal, however, more particularly in smaller examples, as is shown by Figure 2; and, in addition, there is frequent irregularity in the inclination of the surfaces. The distance between the crests of successive rings varies with the diameter of the whole structure, for it is much less in small examples than in large. A further feature is that the inclination of the fracture surfaces is reduced toward the periphery of each structure. Occasionally, the direction of inclination of what appears to be one and the same surface is reversed at opposite ends of a diameter (Fig. 1).

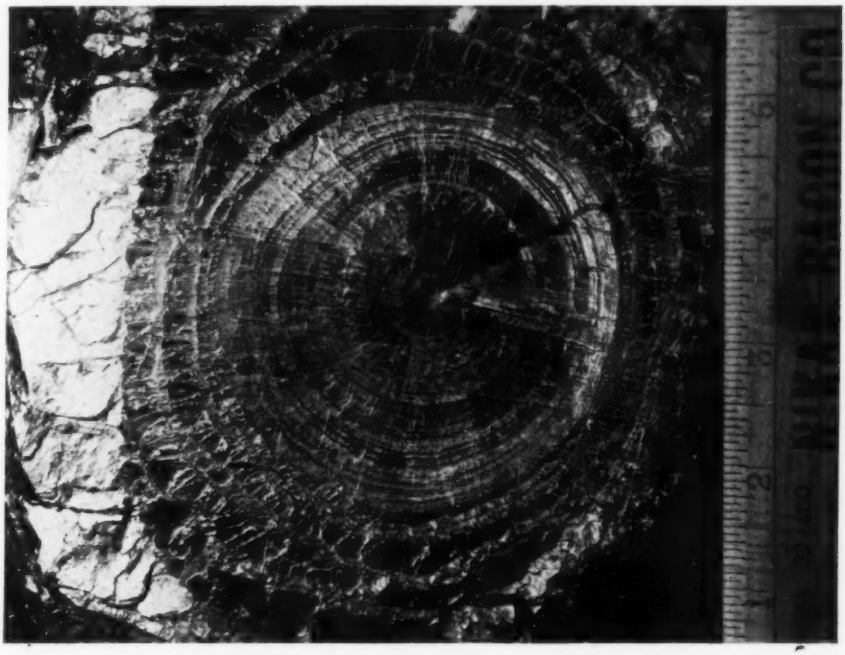

FIG. 1.—Large example of bird's-eye coal, Boote and Party's mine, Greymouth. ×0.6. (Photograph by J. A. Bartrum.)

In the description of "eyes" given by Stutzer and Noé[6] there is no clear reference to ridges such as characterize the Greymouth specimens, although these authors state that Zinchen in 1877 re-

[6] *Op. cit.*

corded fine concentric furrows crossed by individual radial ones, while the "eye" of Figure 69 of Stutzer and Noé appears identical in nature with those from Greymouth. In addition, according to these authors,[7] Weiss in 1869 noted that there is a central point in the "eyes" around which there are often several circular zones which "are bent like the rim of a plate."

The concentric rings are shallow but by no means purely superficial phenomena, as is indicated by Figure 2; yet the larger and more regular examples are developed best where the cleat is strongly shown and yields almost plane fracture surfaces. These large ring systems are almost at right angles to the bedding, which is clearly defined by very thin layers and lenses alternately of bright and dull coal, but small examples may occur in diverse situations and often cluster in varied attitudes about larger individuals (Fig. 3).

Though not entirely superficial, the rings are equally not cross sections of concentric spheroidal shells, for with care one may split a specimen along a parting close and parallel to the main surface and find no trace of the upper set of rings; indeed, an entirely unrelated "eye" may appear. Nevertheless, where close-spaced parallel cleaved surfaces exist, occasionally it is possible to find coaxial rings on these parallel partings at intervals of

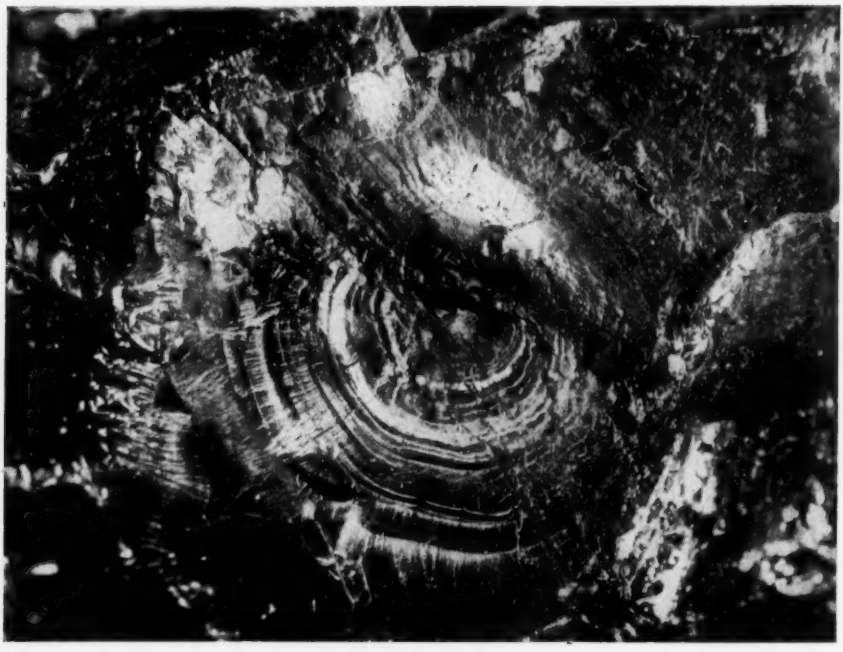

FIG. 2.—Prominent conoidal fracture surfaces in a small "eye," Boote and Party's mine, Greymouth. ×7.4. Minute radial cracks are obvious both in the "eye" and in fringing matrix. (Photograph by J. A. Bartrum.)

[7] *Ibid.*, p. 250.

from 1 to 2 mm. below the uppermost surface, as in the V-shaped sector of Figure 1.

In four of the many dozens of structures examined there are tiny blebs of resin near the centers of the rings; in one instance the bleb is flattened, and its length (2.5 mm.) lies parallel to the bedding and has caused corresponding elongation and ellipticity of the central portion of the rings. On the other hand, similar pellets of resin also occur independently of rings, so that there can be no important genetic relation between their presence and rings except that, if situated close to the point of application of the stresses responsible for the fractures, they probably have determined the precise location of the centers of the ring systems. In a few instances these centers demonstrate either minute conical elevations or else similarly shaped depressions.

There are different degrees of departure from ideal circular form of the rings. In one example the rings of two closely adjacent systems have been crowded against an intervening grain of pyrite and each other. In other cases there is no apparent cause of irregularity, whether it be for the spiral form of Figure 4 or for the more complex asymmetry of Figure 6. The subject of Figure 5 is peculiar in that, with a few others of its kind, it is circumscribed by a single, strongly marked fracture with at most only faint traces of inner rings near the periphery.

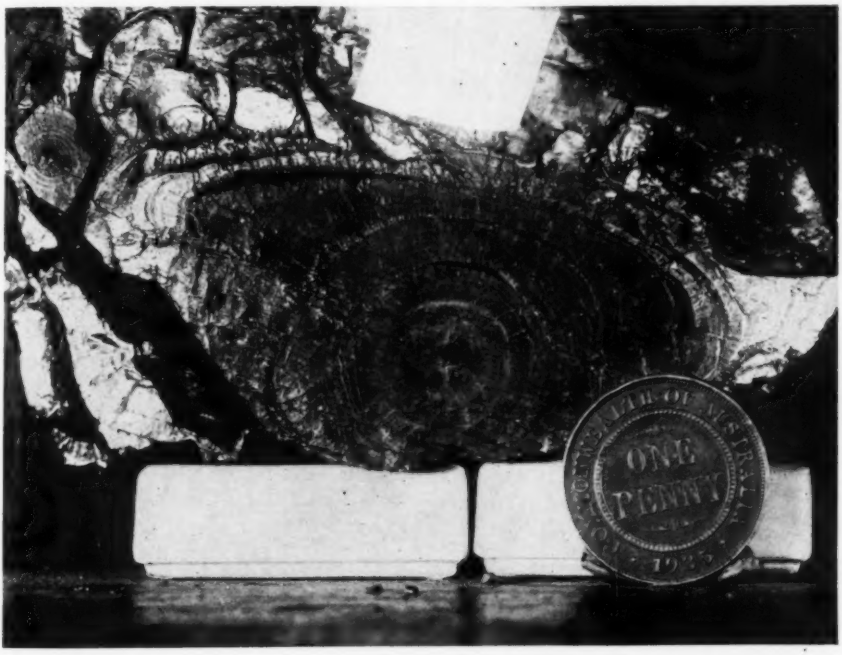

FIG. 3.—Elongated larger "eye" with a peripheral fringe of very small ones, two of which are visible in the upper left corner. Boote and Party's mine, Greymouth. ×0.8. (Photograph by J. A. Bartrum.)

Structures of this class may exhibit on the relatively plane surfaces exposed a film of white deposit which proves to belong to the clay group of minerals and appears also in adjacent minute discontinuous joint crevices.

It is to be noted, finally, in connection with the "eyes" that radial as well as concentric fractures are ubiquitous, as is the case also with those described by Stutzer and Noé,[8] although few are as prominent as those illustrated in Figure 2. They have precisely the same relation to the conoidal fractures that are believed by the writers to cause the rings as obtains in artificially produced percussion cones in such materials as flint and obsidian.

[8] *Ibid.*

MODE OF ORIGIN OF "EYES"

Stutzer and Noé[9] state that pitch coal, representing coalified wood, most commonly exhibits "eyes," although they appear also in brown coal and other varieties. At Häring in the Tyrol, according to these authors, Tertiary pitch coal shows "eye" structure in excellent development near faults. Similar relations exist near Greymouth for Boote and Party's workings, where the "eyes" are abundantly and perfectly developed, lie upon the relatively broad crest of a plunging anticline within a narrow elongated tapering block between two converging members of a series of normal step faults, the apex being truncated by a third and considerably larger fault.

[9] *Ibid.*

FIG. 4.—Spiral ring structure, Boote and Party's mine, Greymouth. ×4.5. (Photograph by J. A. Bartrum.)

Faulting is also pronounced adjacent to the few other mines where comparable structures are evidenced. Proximate analyses, without being conclusive, indicate that type of coal probably also is important in the development of "eyes," for less closely jointed phases of the bituminous coal general in the district at most sent from coals 700–800 feet stratigraphically below the seam worked by Boote and Party. Considerable vertical compression has, however, been in operation, for the thickness of the whole succession of Tertiary strata in the region, omitting those of Pliocene age, formed mainly after the folding and faulting, averages about

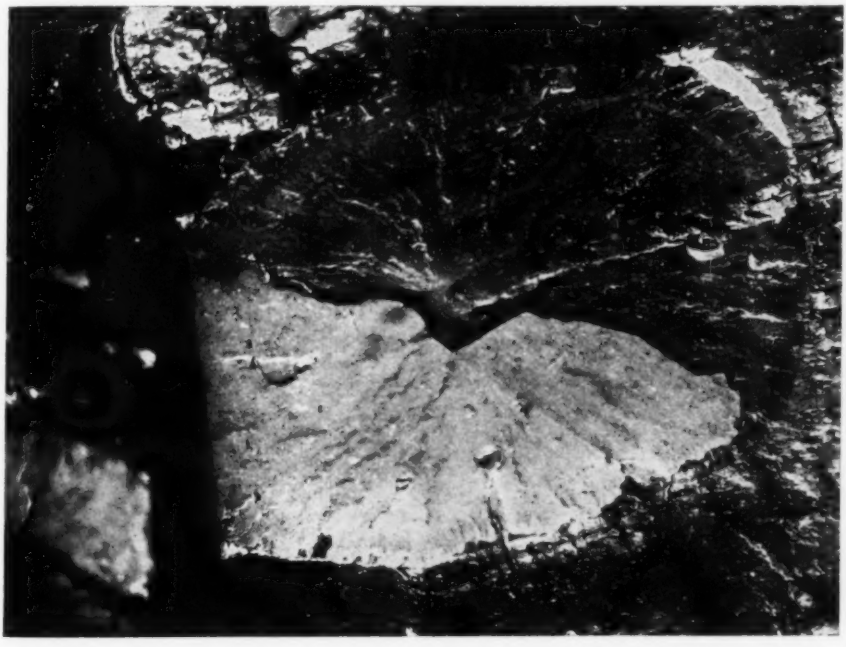

FIG. 5.—Unusual type of "eye," Boote and Party's mine, Greymouth. ×4.4. (Photograph by J. A. Bartrum.)

have yielded poor examples of the structures, and the best come only from very closely cleated coal somewhat distinct from the others in analysis. This appears to have reacted differently from other varieties to the operating stresses, which have been of much the same order and kind throughout the whole coal field. Increased depth of cover, whether past or present, has not determined the presence or absence of the "eyes," for they are absent from coals 700–800 feet stratigraphically below the seam worked by Boote and Party. Considerable vertical compression has, however, been in operation, for the thickness of the whole succession of Tertiary strata in the region, omitting those of Pliocene age, formed mainly after the folding and faulting, averages about 9,500 feet.[10] The Paparoa beds which contain the "eye" coal are the basal members of this succession. Thus, in considering the origin of the ring structures, it is to be noted that horizontal compression has been aided by important vertical pressure.

Early writers suggested that the "eyes" are the result of shrinkage during consolidation of the coal, but Stutzer and

[10] Morgan, *op. cit.*, pp. 51 and 62.

Noé[11] favor the view of Hofmann, published in 1910, that they occur only in very homogeneous brittle coals affected by disturbances near at hand and that they are nothing more than unusual cleavage or fracture planes. The conclusion of these writers may well be quoted:

In the limited literature available to the writers of this paper no consideration is given to the presence of what appear definitely to be conoidal shears evidenced in specimens such as that of Figure 2 or to the reversal of slope noted on either side of the crest of each ring of these

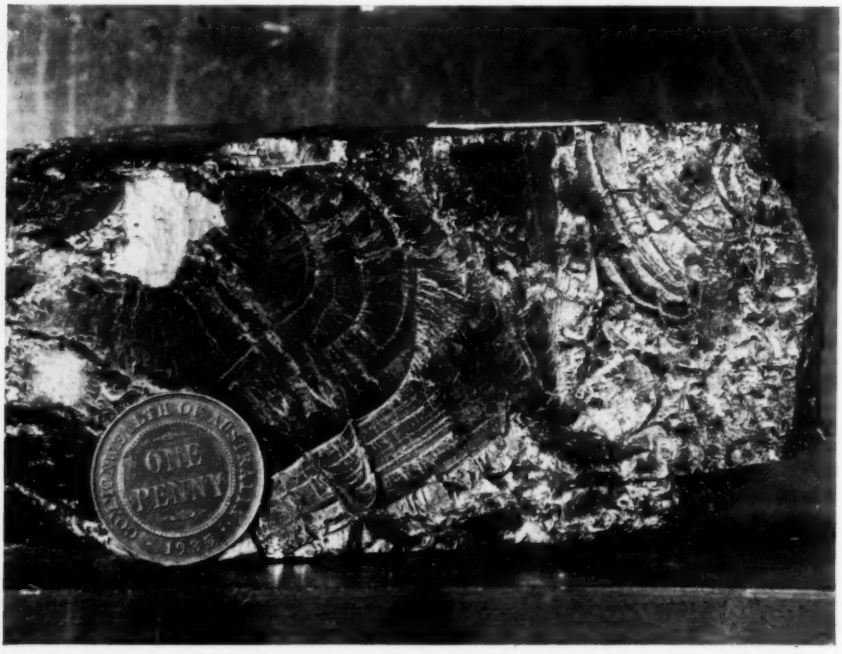

FIG. 6.—Irregular structure in coal from Dobson Mine, Greymouth. ×0.7. (Photograph by J. A. Bartrum.)

We agree with Hofmann (1910) that the origin of eye-coal is due to pressure. Eye-structure is caused by the same forces that produce cleat and slate fracture. The plane of the "eyes" is therefore always parallel to the cleat produced at the same time and is normal to the direction of pressure. Eye-structures may be found also in other rocks. They are known in the shales of the Upper Permian (Zechstein) near Eisleben. The eye-structures of this shale lie in parallel planes running at a right angle to the lamination. These "eye-shales" must have had an origin similar to that of the eye-coals.[12]

structures. With diffidence based on their ignorance of the principles of the mechanics involved, the writers proffer two alternative hypotheses of origin which involve conoidal shearing in conjunction with stresses of the type that creates the normal cleat of coal.

Assuming that the surfaces on either side of the crest of a ring are due to such conoidal shearing, explanation of the high angle of inclination of these surfaces with reference to the axes of the cones

[11] *Op. cit.* [12] *Ibid.*, p. 253.

must be sought, for it is much in excess of the 45° theoretically characteristic of shear developed by compression of homogeneous material. According to Professor T. D. J. Leech, of the School of Engineering, Auckland University College, who kindly made a mathematical analysis of the problem, such high-angle shears may originate, should vertical and compressive shearing forces both operate.[13] It is suggested with hesitation that conceivably the same result also may be attained should the material on which such forces act be composed of thin plates normal to the axes of the shear cones.

As a first hypothesis it is suggested that the concentric fractures are the result of compressive forces of diastrophic origin which gave rise to sheared close-spaced surfaces nearly normal to the bedding and of closely localized impact brought into being by the faulting that has been shown to characterize the region. Differential movement along planes of shear would cause salients from one surface of a fracture here and there to come to rest against opposing elevations from the other surface. Saltatory movements connected with the faulting would cause impact at such points, so that high-angle (with axes of resulting cones) conoidal shears might be developed with axes at right angles to the planes of lateral shear that bounded any particular layer considered. It is suggested further that closeness of cleat allowed the existence of a number of layers sufficiently thin to permit flexing under impact. In consequence, localized impact would be transmitted from layer to layer and a series of conoidal shears of varied angle such as is roughly represented in Figure 7 would be formed, all coaxial but each set of cones opposed in direction to the next. Exceptional weakness would exist in a zone of commingling of the conoidal shears entering from opposite surfaces of a layer of coal and a substantially contemporaneous lateral shearing force would then create a median zone of shears each member of which would be comparable with *AA* in Figure 7, for yielding would be likely to occur along the commingled conoidal shears, which are alternately reversed in direction, as is the case with the ridges that constitute the rings of the ring fractures. Some actual fracture might occur during the inci-

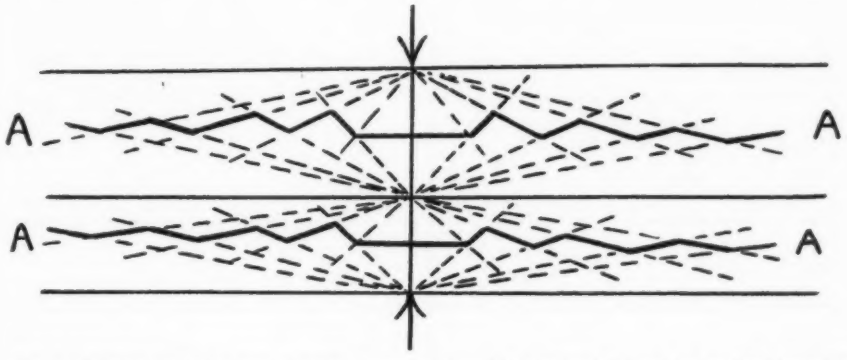

FIG. 7.—Section parallel to axis of series of cones of shear likely to be developed by localized impact in pile of parallel flexible and highly elastic thin plates.

[13] Personal communication.

dence both of impact and of lateral shearing, although it is not essential to the hypothesis that this be so; it could well be delayed until compressive crustal stresses were replaced by tensional ones or even until mining operations brought about unbalanced forces at the faces of excavations. Under ideal conditions, namely, homogeneity of material and incidence of impact perpendicular to the cleat layers of coal, the pattern of the conoidal fractures in sections perpendicular to the cone axes would be circular, as in the typical ring systems. Departure from ideal conditions would cause the irregularity illustrated in some of the figures.

The group of structures represented by Figure 5, however, seems to demand a special explanation for the single definite circumscribing fracture. They occur in coal that lacks the well-developed cleat that is associated with the large concentric ring systems. It may be assumed, therefore, that local conditions in these cases may have allowed the protection of such coal from the full severity of lateral pressure manifested elsewhere, so that layers of coal affected by perpendicular impact would be relatively thick and would, therefore, develop percussion cones with a single surface of rupture such as may be produced artificially in materials like flint or obsidian.

An alternative hypothesis of origin follows that just outlined to the stage when, after preliminary differential movement along a surface of shear, impact is created by faulting movements and conoidal shears develop; in this case, however, it is suggested that they are less complex. Two sets of opposed cones are imagined to be produced at each point of contact, one set on either side of a shear surface (Fig. 8). If the layer of coal has substantial thickness, these are likely to be the only cones created, and concentric rings of shear will appear on the more or less plane surfaces of contiguous shear layers. The reversals of directions of "cleavage" so characteristic of the ring systems cannot appear on such surfaces, and its failure to explain such reversals is a weakness of the theory. It is possible, however, that subsequent rupture of the coal by tension or other cause along sealed shear planes adjacent and subparallel to

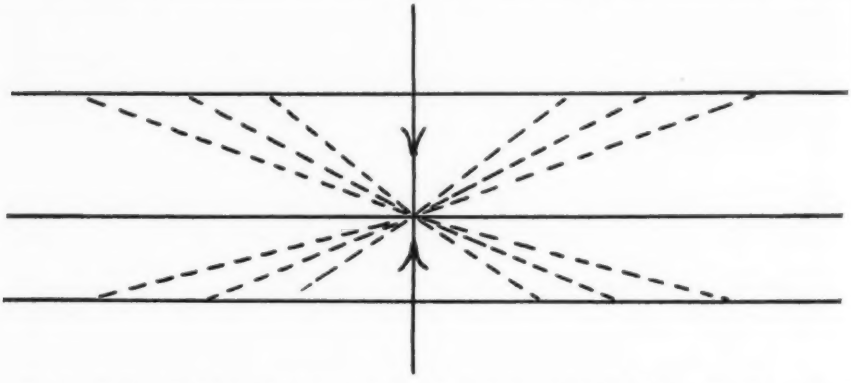

FIG. 8.—Section parallel to axis of cones of shear likely to be produced by impact in adjacent poorly flexible thicker plates.

the early-opened main shear planes may create such reversals when such planes intersect conoidal shears.

CONCLUSION

Perfect examples of eye structure in early Tertiary bituminous coal have been described from Greymouth, New Zealand, by the authors, who believe that their origin is bound up with the local formation in coal of almost homogeneous nature and special physical character of conoidal shears by compressive forces acting both horizontally and vertically. The hypotheses of origin proffered attempt to explain certain peculiarities of the concentric rings that comprise the "eyes."

ACKNOWLEDGMENTS.—Thanks are due to Professor W. N. Benson, of Otago University, and to Professor T. D. J. Leech, of Auckland University College, for material assistance in the preparation of this paper and, finally, to Messrs. Henry Loeb and J. R. Leitch for supplying the specimens studied and photographed.

STONE-CENTERED POLYGONS[1]

GEORGE ROZANSKI
443 Cyprus Place, New York City

ABSTRACT

Upended shale fragments as herein described form a pattern resembling the stone polygons of arctic and alpine regions. Unlike most northern occurrences, these fragments lie on bedrock, and clay is practically absent.

INTRODUCTION

Stone-centered polygons occur on the rock ledges bordering the Genesee River at Letchworth Park, New York, and appear to best advantage in a 30 × 50-foot area northeast of Portageville (Figs. 1 and 2). The phenomenon is discontinuously developed over this area. The Genesee River is here actively downcutting in flat-lying, thin-bedded Devonian Gardeau shale. The rock bank is topped by a resistant bed about 4 inches thick (Fig. 2, left background) and slopes gently to the stream channel. Inland is a small swamp, and seepage from this crosses the ledges upon which the polygons are found.

DESCRIPTION OF THE STONE-CENTERED POLYGONS

The stone-centered polygons consist of slabs of shale approximately 1 foot in diameter and 3–4 inches thick, around which are arranged fragments of fresh, dark-gray thin-bedded shale averaging 3 inches in length, somewhat less in width, and up to $\frac{1}{4}$ inch in thickness. Most of the fragments stand nearly vertical, but some lie flat. The pieces lie parallel to the sides of the large slabs, radiate as if from a center, or lack definite patterns. Usually they rise above the central block, but not markedly so. All are tightly packed and complexly interlocked (Fig. 3). Vegetation is absent. Excavation showed that the upright surface fragments meshed with others beneath, also in vertical position. Usually less than the equivalent of two layers was present.

The small upright fragments were derived exclusively from the rock ledges upon which they rested. The central slabs were river boulders or local rock. It seems that the presence of river boulders as "centers" is purely fortuitous. Within a total distance of 200 feet, including, and on both sides of, the area under discussion, only thirty-six stream boulders were observed. These occurred among the blocks of local derivation.

Twenty-eight stone-centered polygons were excavated (Fig. 5). Bedrock was reached within 6 inches in most of the excavations—usually less. The procedure was to remove the center block (Fig. 6), clear away the slump and note the appearance, and then continue to bedrock (Fig. 7). In all cases the center block accounted for more than half the depth of the excavation. In two cases it was found to rest on fine mud and sand, in fourteen on a mixture of sand grains and shale flakes of various sizes (Fig. 6), and in the remaining twelve bedrock was visible immediately beneath the slab (Fig. 8). In the latter cases fine material was almost lacking; but commonly a scattering of clay, sand, and shale flakes was present.

[1] The results of this study are published with the permission of the National Park Service, but the writer assumes full responsibility for the contents.

Most of the excavations were wet from the swamp seepage.

Some of the mud is probably brought in by the swamp seepage, some is derived in place, and the remainder comes from the river, which also supplies the sand. The shale flakes are derived in place from either the bedrock or the overlying slab.

In a number of excavations the surface of the bedrock was irregular, sloping away from the river. Such a bottom configuration has significant water-holding properties. Fine material was present in the deeper portions, so that the center slab rested level or practically so (Fig. 6).

Some noncharacteristic arrangements were noted in the same area. Large rectangular blocks of local origin, 3–4 inches thick, were scattered over the bank. Eleven of these had shale packed against one or two sides—even on gentle slopes. Most of these blocks rested upon a heterogeneous mixture of sand, mud, and shale

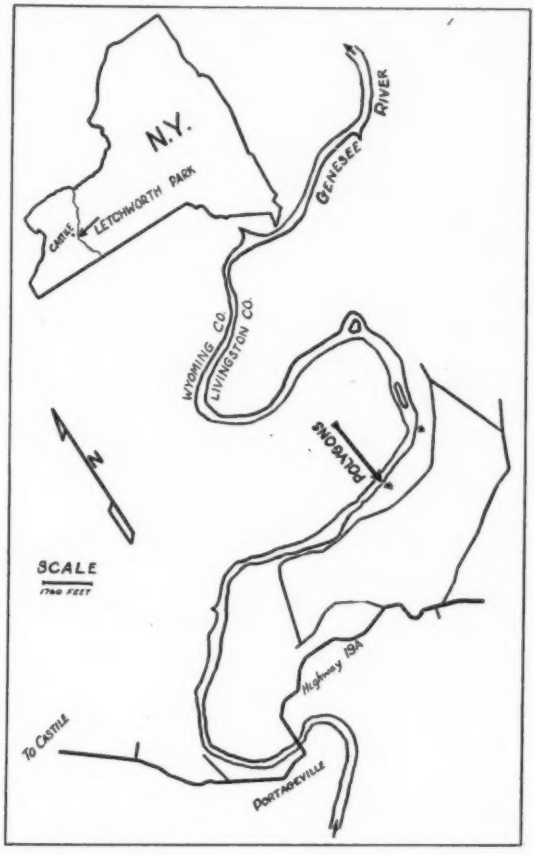

FIG. 1.—Key map showing location of stone-centered polygons (*arrow*) in Letchworth Park, New York

particles. A few large blocks appeared to have been washed upon an irregular pattern of vertical fragments previously formed. These irregularities are the result of variations from the most favorable conditions of formation and are to to be expected.

METHOD OF FORMATION

The Letchworth polygons are believed to have been formed by water seeping in from the swamp and freezing in the cracks of the well-jointed and thin-bedded Gardeau shale. Each time ice was formed, the flat-lying rock was buckled upward until it broke. Later more water and some mud accumulated between the pieces. When this water froze, it spread laterally and upward, but near the surface the greatest relief was upward. The ice therefore forced its way up through the fragments, spreading and wedging them apart. When the ice melted, the fragments were unsupported but did not fall flat because they were packed too tightly. As the process continued, there was further fragmentation and more small material produced. Concurrently with the increased crowding, capillary forces caused the water to rise between the tilted fragments. In this position the water became more effective in raising the pieces from the horizontal when it froze. Whatever mud was present helped by facilitating the formation of needle ice, as described by S. Taber.[2] Occasionally a piece was pushed out on the surface and fell flat on the others. In time there was formed a mosaic of interlocking fragments standing on edge, some as much as 14 inches long. If large blocks were present, the fragments were packed around them or radiated from them. Where several such blocks were present, a pseudo-

FIG. 2.—General setting of Letchworth Park stone-centered polygons. Hat for scale

[2] "Frost Heaving," *Jour. Geol.*, Vol. XXXVII (1929), p. 428.

FIG. 3.—Stone-centered polygons at Letchworth Park, New York. Watch for scale

FIG. 4.—Gregory's figure of the Loch Lomond occurrence reproduced with the permission of the Royal Geographical Society. Rule 9 inches long.

polygonal pattern was formed having stone centers.

If the process were continued without interference, the entire area should be fragmented and upended by frost action. The earliest-formed pieces should be progressively reduced to mud. Thus a heterogeneous mixture of clay and stones would be formed which might give rise to true stone polygons. At Letchworth such an end product would never form because the river washes out the mud as fast as it accumulates.

FIG. 5.—Undisturbed stone-centered polygon. Center block level. Pencil for scale.

FIG. 6.—Central block lifted out. Note undisturbed lower surface. Near end of pencil rests on bedrock covered by water.

RELATED STRUCTURES DESCRIBED IN THE LITERATURE

Study of the literature reveals resemblances between the Letchworth Park phenomena and some of the stone polygons from arctic and alpine areas which have been attributed to frost action.[3]

J. W. Gregory[4] has described and figured stone polygons from the eastern side of Loch Lomond which are strikingly similar to those at Letchworth. These are composed of slate which has accumulated on the shore from a quarry that was last worked in 1879. Gregory's Plate 2 is here reproduced as Figure 4. Gregory reported that the fragments were packed about boulders and tree trunks as well as slabs. The polygonal form occurred in a minority of examples, but he considered the structure similar to the stone polygons which he had seen in the arctic. He stated:

> The essential factors for stone-packing and the formation of stone-polygons are loose ground containing or composed of flat pebbles; the ground must be sodden with water; and it must be frequently frozen and thawed, so as to be acted on by repeated horizontal thrusting.

[3] C. F. S. Sharpe, *Landslides and Related Phenomena* (New York: Columbia University Press, 1938); see Bibliography.

[4] "Stone Polygons beside Loch Lomond," *Geog. Jour.*, Vol. LXXVI (1930), p. 415.

E. Antevs[5] reviewed the Loch Lomond observation and considered that a high water table, combined with sufficient freezing and thawing, would be sufficient for the formation of the polygons.

S. E. Hollingworth[6] thought that Gregory's examples were "possibly of distinct origin."

J. S. Huxley and N. E. Odell[7] concluded from their studies in Spitsbergen that

FIG. 7.—All loose material removed. Note shallow depth to bedrock.

the processes leading to the formation of stone polygons could be initiated in live rock as well as in heterogeneous materials.

C. S. Elton[8] described a number of stages from one small area, also in Spitsbergen, which he believed demonstrated the derivation of mud polygons from stone polygons as follows:

a) Weathering red shale thrown up into hummocks about a foot high
b) Rock of such hummocks weathered into upright stones with no mud-centre
[*c*) Small mud-centre, with a ring of upright stones]
d) Larger mud-centre, with smaller shale border: typical stone-polygon
[*e*) Further reduction of the shale border]
f) Disappearance of shale border, so that a mud-polygon resulted

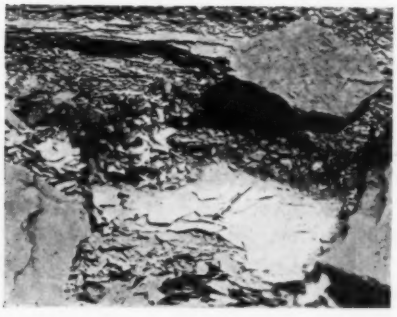

FIG. 8.—Bedrock exposed in another excavation

The foregoing are selected examples bearing upon the present discussion. As commonly described, stone polygons consist of a central area of mud surrounded by a polygonal border of uptilted stones. They are found on level ground and are believed to have formed from a heterogeneous mixture of saturated clay and stones.

GEOGRAPHICAL DISTRIBUTION

In all hypotheses which have been offered for the formation of stone polygons and related structures the dominant factors have been taken to be freezing and thawing and adequate water. These conditions are satisfied in temperate, as well as in arctic and alpine, climates. We should therefore expect to find stone

[5] *Alpine Zone of Mt. Washington Range* (Auburn, Maine: Merrill & Webber Co., 1932), p. 58.

[6] "Some Solifluction Phenomena in the Northern Part of the Lake District," *Proc. Geol. Assoc. London*, Vol. XLV (1934), p. 168.

[7] "Notes on Surface Markings in Spitsbergen," *Geog. Jour.*, Vol. LXIII (1924), p. 220.

[8] "The Nature and Origin of Soil-Polygons in Spitsbergen," *Quart. Jour. Geol. Soc. London*, Vol. LXXXIII (1927), pp. 172–73, 183.

polygons in temperate climes; and they have, in fact, been reported.

J. B. Simpson[9] described stone polygons at an elevation of 1,873 feet near the summit of Ben Iadain, Morvern, Argyllshire, Scotland. He noted that this locality did not have the severe climate and low temperatures of the usual arctic and alpine occurrences. Hollingworth[10] concluded that the features he studied in the Lake District of England in an area ranging in elevation from below 500 feet to above 3,000 feet were of recent origin. In a footnote at the end of his paper Gregory[11] stated that he had received photographs of "stone rings" similar to those described by himself from Mr. J. Selwyn Turner, F.G.S. These had been formed between tidemarks at the head of Bantry Bay, southwest Ireland. They were composed of debris from an old slate quarry.

In the United States Antevs[12] has described stone polygons from Maine, New Hampshire, and Colorado; but these are in many respects alpine occurrences. H. W. Leavitt and E. H. Perkins[13] recognized them in Maine; R. P. Goldthwait[14] measured the yearly movement of markers inside of stone polygons in the same state. C. S. Denny[15] describes "stone-centered rings" from New Hampshire mountains. R. L. Nichols and F. Nichols[16] have noted stone polygons on Mount Desert Island, Maine, at elevations of 1,100 and 1,300 feet. Robert P. Sharp[17] noted "crude but distinct stone rings" at 11,600 feet (above timber line) near Agassiz Peak, San Francisco Mountain, Arizona. He states that frost action is effective in this area. This location, 9 miles north of Flagstaff, Arizona, is farther south than the poorly developed polygons noted by the writer in North Carolina (see below). C. H. Hitchcock[18] wrote of "curiously arranged" fragments of slate along Lake Champlain, Vermont. His woodcut resembles a stone-centered polygon. At Letchworth Park these structures are found between elevations of 715 and 760 feet.

H. M. Eakin[19] described segregations of gravel and soil having a reticulated pattern from the vicinity of Olympia, Washington, at an elevation probably between 500 and 1,000 feet. He thought that these had formed during a period of periglacial climate. These may still be active during unusually cold periods. Antevs[20] stated that vegetation was usually lacking in the modern stone polygons on Mount Washington but was present in the "fossil" structures. Eakin does not discuss the vegetation in his description.

In March, 1942, the writer observed poor examples of a stone-centered polygon (*S*) and mud-centered stone polygons (*M*) near the east flank of the Great Smoky Mountains in North Carolina at an elevation of approximately 1,820 feet (Fig. 9). Excavation of the stone-cen-

[9] "Stone-Polygons on Scottish Mountains," *Scot. Geog. Mag.*, Vol. XLVIII (1932), p. 37.

[10] *Op. cit.*, p. 180.

[11] *Op. cit.*, p. 418.

[12] *Op. cit.*, pp. 48–52, 55–58.

[13] "Glacial Geology of Maine," *Maine Tech. Exper. Sta., Bull. 30*, Vol. II (1935), p. 216.

[14] "Geology of the Presidential Range," *N.H. Acad. Sci. Bull. 1* (1940), p. 40.

[15] "Stone-Rings on New Hampshire Mountains," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), p. 437, and Pl. I.

[16] "Polygonboden on Mt. Desert Island, Maine," *Sci.*, Vol. LXXXIII (new ser., 1936), p. 161.

[17] "Multiple Pleistocene Glaciation on San Francisco Mountain, Arizona," *Jour. Geol.*, Vol. L (1942), p. 499.

[18] *Geology of Vermont*, Vol. I (1861), p. 63 and Fig. 25.

[19] "Periglacial Phenomena in the Puget Sound Region," *Sci.*, Vol. LXXV (new ser., 1932), p. 536.

[20] *Op. cit.*, pp. 51–52.

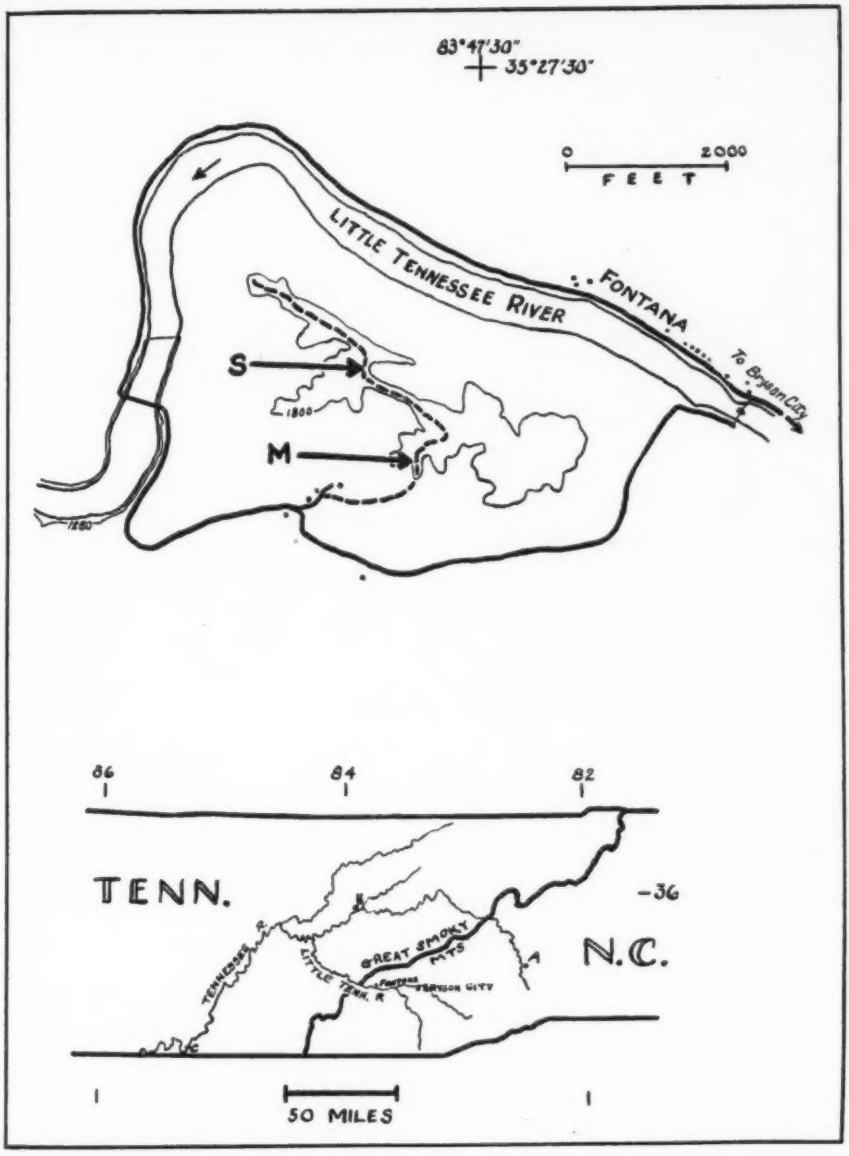

FIG. 9.—Location of a stone-centered polygon (*S*) and mud-centered stone polygons (*M*) near Fontana, North Carolina.

tered polygon (Fig. 10) revealed that the central slab was underlain by a layer of wet clay, which in turn lay on another slab 3 inches thick. The central slab and vertical elements were of phyllite and were embodied in clay. Excavation of the stone polygon (mud center) to a depth of 3 inches found clay and some stones without apparent arrangement (Fig. 11). These examples were found in a dirt road along a divide. This road carried no vehicles during the winter and very few foot travelers. The structures must have formed during the winter. Vegetation was not present.

FIG. 10.—Stone-centered polygon near Fontana, North Carolina

During this same winter the writer frequently observed needle ice[21] lifting stones, some as large as a man's hand, in this and other areas. Where many stones were available, some were heaped on top of others. Needle ice was prevalent on bare ground, the needles being always perpendicular to the surface, even in steep roadcuts. Needle ice was not seen in association with the incipient polygons discussed above.

It is interesting to note that the areas mentioned in Great Britain and the United States are slowly pushing the known occurrences of stone polygons toward the southern limit of the temperate zone.

DISCUSSION OF TABLE 1

Since the formation of stone-centered polygons and stone polygons probably

[21] Taber, *op. cit.*

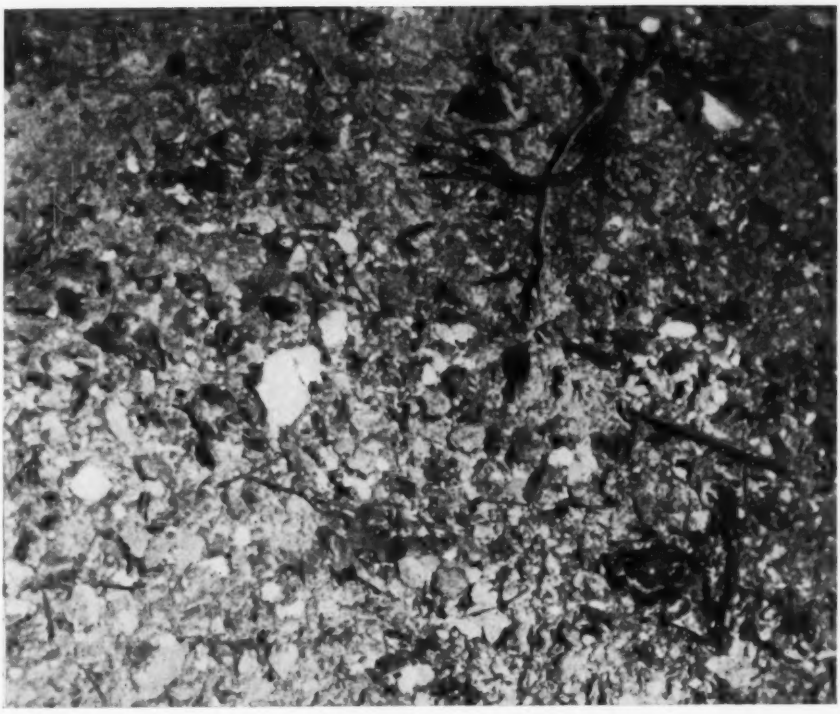

FIG. 11.—Poorly developed mud-centered stone polygons. Some stones have been pushed into an upright position and incipient centers cleared of larger flakes—for example, to left of pencil.

TABLE 1

NUMBER OF DAYS TEMPERATURE CROSSED THE FREEZING-POINT (NO SNOW ON GROUND), LETCHWORTH PARK, NEW YORK*

Month	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	Average
Jan.	15†	18†	22	15	5	3	22	1	2	1	10.4
Feb.	22†	11†	14	n.d.‡	7	2	12	13	0	0	8.1
Mar.	16†	13†	19	22	16	15	15	9	5	0	13.0
April	12†	18	8†	14§	13	17§	10§	3	15	15	12.5
May	1	3	1	3	5	4	n.d.	1§	4	2	2.4
Sept.	n.d.	1	n.d.	n.d.	1	1	0	n.d.	n.d.	n.d.	0.3
Oct.	4	2§	8§	8	7§	9§	9	4	6§	9§	6.6
Nov.	8	19	10	11	12†	11	9	4	18	9	11.1
Dec.	16†	11§	11	12	3	9	2	6	13	9	9.2
Total	94	96	93	85	69	71	79	41	63	45	73.6

* Based on actual readings of snow depth on the ground at time of temperature reading. Only daily maximum and minimum temperatures were used in the construction of this table.

† Only total daily snowfall known. Number of days an interpretation, obtained by comparing this month's readings with similar information from periods having known snow depths at time of temperature observation.

‡ Data for this month not available to the writer.

§ Traces of snow recorded this month. No depth measurements taken at time of temperature observation.

depends upon temperature fluctuations across the freezing-point, quantitative information is important. The daily weather reports made by the co-operative weather observer at Letchworth Park[22] have therefore been tabulated for a 10-year period and are presented as Table 1.

Table 1 shows the number of days during each month that the temperature crossed the freezing-point with no snow on the ground. Days during which the freezing-point was crossed but the ground was snow covered were not included, because the snow formed a refrigerated blanket which kept the ground beneath frozen. Only during periods of recurrent freezing is ice formed and stones moved. The process is inactive in continuously frozen ground.

Direct readings of the amount of snow present on the ground each day are available for 61 months of the 82 tabulated. For the remaining 21 months, only the amount of snowfall and the day it fell are known. Only a "trace" was recorded for 11 of these 21 months. In the table a "trace" was considered an effective refrigerative blanket for one day, which is a liberal assumption. For the remaining 10 months, when more than a "trace" was recorded, the amount of snowfall and the temperature on that and following days were compared with similar data for a month in which daily snow depths were known. In this way the probable duration of the snow cover was determined.

The table gives the total number of days the temperature crossed the freezing-point for each year, the average per month for 10 years, and the average number per year for the 10 years—73.6 days. It should be noted that this figure is in days. No account has been made of daily fluctuations.

The table is subject to the following errors: The effect of salts in solution in the ground water was disregarded. These may lower the freezing-point of the soil from 2° to 9° below 32°, according to Dr. C. F. Brooks.[23] (2) In autumn the latent heat of the ground counteracts the first frost. (3) The temperatures were not taken at ground-level and therefore do not record the coldest layer next to the ground. (4) Evaporation accounts for almost as much loss of snow as thawing. It is not believed that these considerations would materially affect the numerical result. However, the temperature may have oscillated around the freezing-point a number of times in any one day.

SUMMARY

Stone-centered polygons, a phenomenon akin to stone polygons, can be initiated and formed in thin-bedded rock without the presence of clay, provided sufficient moisture is present. Both types of polygons may be found wherever the temperature varies around the freezing-point for a few months of every year. The Letchworth type may be a preliminary stage to the mud-centered variety in areas of bare rock. The observations of Huxley and Odell[24] and of Elton[25] lend credence to this view.

At Letchworth an average year will have 73.6 days of effective freezing and thawing temperatures. Actually the temperature may have oscillated across the freezing-point more than once during each one of these days.

For all practical purposes one winter

[22] *U.S. Dept. of Agric., Weather Bureau, Co-operative Observers' Meteorological Record Jan. 1931 to Dec. 1940, Letchworth Park, Wyoming County, N.Y.*

[23] G. S. Lindgren. Personal communication, 1941.

[24] *Op. cit.*

[25] *Op. cit.*

may be considered the minimum period for the formation of polygonal structures. Colonel H. W. Feilden[26] reported that a gravel patch near his home in Burwash, Sussex, England, showed miniature polygons after every winter. Denny[27] thought that stone rings at the base of a fire tower are reformed every year or two. Sharp[28] found stone rings on a road 8 years after it had been abandoned. In North Carolina the writer observed poorly formed stone polygons and a stone-centered polygon in an undeveloped dirt road that had not been used during the winter.

At Letchworth Park the phenomenon originally photographed by the writer had been replaced by new structures 4 years later after approximately 300 days of freezing and thawing temperatures. This is probably a maximum figure. We now have for this temperature zone a working estimate of the maximum and minimum times required for the development of these features. This is open to further investigation.

It would be interesting to learn how many days during the year freezing temperatures are effective on bare ground in the arctic and alpine areas from which stone polygons have been reported.

ACKNOWLEDGMENTS.—Through the kindness of Mr. G. S. Lindgren, meteorologist in charge, at the Weather Bureau Office in Albany, New York, the data of the co-operative weather station at Letchworth Park were made available to the writer. The assistance of Mr. Frank Gemmill, of the New York City Weather Bureau, is also acknowledged.

[26] "Trevor-Battye, Aubyn: A Theory of the Origin of Surface-Polygons in Polar Lands," *Geog. Jour.*, Vol. LVIII (1921), p. 308.

[27] *Op. cit.*

[28] *Op. cit.*, p. 500.

DISINTEGRATING SOIL SLIPS OF THE COAST RANGES OF CENTRAL CALIFORNIA

JOHN E. KESSELI
University of California

ABSTRACT

On relatively gentle slopes of the Coast Ranges of central California the debris involved in soil slips frequently breaks up into clods immediately after slipping has started, instead of remaining together and forming a bulging tongue. A group of such slips, here called "disintegrating soil slips," is pictured and described, and their origin is interpreted.

INTRODUCTION

Among the many forms of denudation commonly termed "landslides" and included in the group of mass movements or processes of mass transfer, a less conspicuous and more ephemeral type, possibly of more frequent occurrence in California than elsewhere, has not received the attention it deserves. For lack of a better descriptive name, it is here called a "disintegrating soil slip." Such small slips are very common in the hills of the Marin Peninsula to the north of the Golden Gate (Fig. 1), where the scars of approximately a hundred were noticed in the course of a few afternoon trips. Although disintegrating soil slips seem to be exceptionally numerous on this peninsula, they occur also in other areas of the Central California Coast Ranges. They were first recognized as a special form of landsliding by E. S. Thomas,[1] who observed a few in the hills east of San Francisco Bay. Thomas called them "pocket slides" because of their small size as well as an inferred causal association with bedrock pockets. This name, however, especially in its explanatory meaning, is deemed less satisfactory than the cautiously descriptive name suggested above. Thomas also discovered that these disintegrating soil slips are of relatively frequent occurrence in the foothills of the Sierra Nevada, where he noticed some twenty-five along the Merced River below El Portal (Yosemite) in the wake of a series of heavy rains.

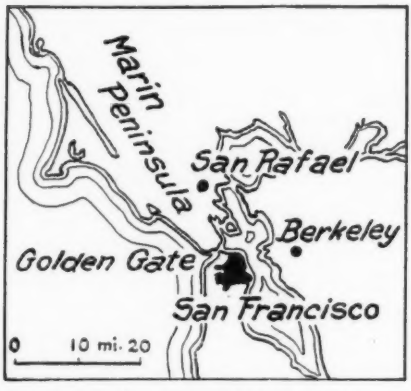

FIG. 1.—Location of Marin Peninsula

None of the features here described was witnessed during formation, although there is reasonable certainty that some of the slips were visited only a few days after they took place. All conclusions concerning their origin are thus, by necessity, inferential.

APPEARANCE OF DISINTEGRATING SOIL SLIPS

Figures 2 and 3 show the appearance of a disintegrating soil slip in a relatively

[1] "Landslide Forms and Their Origin in the Middle Coast Ranges" (unpublished Master's thesis, University of California, 1939), pp. 13–19.

fresh state. At its head is a depression from which the scattered material originated, very similar in appearance to the break-away scarp of a slump[2] or earth-

FIG. 2.—Disintegrating soil slip in a fresh state. Pacheco Hill, on U.S. Highway 101, 4 miles north of San Rafael.

flow. The dimensions of the source depression of this soil slip were 24×18 feet. Its greatest depth was 5 feet. The floor of the depression dipped outward at an angle of about 10°. No bedrock was seen in the depression. A near-by roadcut showed the hill to be carved from shales and sandstones. The tongue-shaped zone of deposition measured 200 feet in length × 25 feet in width. The material from the excavation was found strewn over the slope below in the form of rounded pieces of sod and subsod soil up to a foot in greatest size. Most pieces were nearly spherical in shape and displayed fairly smooth surfaces, clearly indicating the effect of rolling in a wet state. In their upper third the edges of the tongue were marked by two lateral ridges, 1–2 feet wide and up to 1 foot in height, composed of subangular pieces of sod and soil held together by mud. Farther downslope, the outline of the zone of deposition became less definite. In the lower third the number of clods was markedly reduced, and only a few indicated the extreme of advance reached. At the point where the slip started, the slope had an inclination of 18°. Where the last rolling pieces of

FIG. 3.—Close-up view of slip of Fig. 2

mud came to rest, the slope inclination measured only 7°.

Figure 4 shows two disintegrating soil slips of recent occurrence covering the trace of an older soil slip. The larger of the two recent slips was the last to break

[2] The term "slump" has been applied to a variety of landslides. In this account it refers to the feature resulting from the sliding of a regolithic cover without loss of coherence, producing a crescent-shaped break-away scarp at its upper end and a slight bulge at its toe.

loose, as indicated by the superposition of its train and its unbroken left lateral ridge. To judge from the preservation of the clods, both slips seem to have occurred on the same day. The two slips originated on a slope of 23° and scattered the rounded clods over a distance of 240 feet on a slope of 18°. The clods were of somewhat smaller size than in the preceding case, measuring no more than 8 inches. The source depression of the larger slip (Fig. 5) measured 20 feet in width and 27 feet in length, the long axis being oriented approximately with the slope. The depth of the regolith removed was nowhere greater than 4 feet. Bedrock was not exposed at the first visit. At a second visit, three months later, subsequent rainwash had uncovered weathered and fractured sandstone *in situ* at different points, although the depression did not seem to have deepened since the first visit. The slip surface thus evolved in close proximity to the upper surface of relatively sound bedrock. The source depression of the smaller slip was shallower—3 feet at the most—and showed no bedrock on the second visit.

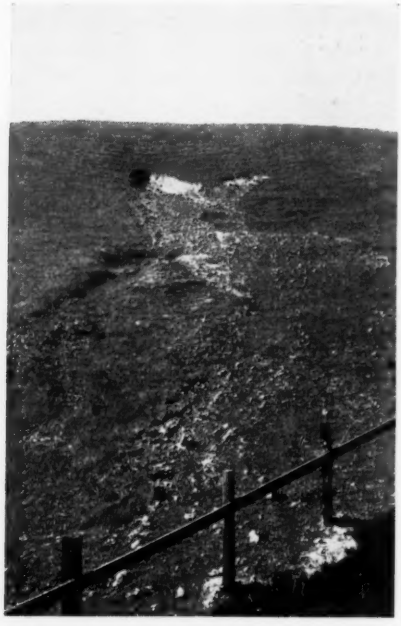

FIG. 4.—Two superimposed disintegrating soil slips which probably occurred on the same day. In left center and lower left the source depression and train of an older slip. Pacheco Hill.

FIG. 5.—View of larger source depression of Fig. 4 from above.

Figures 6 and 7 show the appearance of a disintegrating slip which started from the head wall of a slope gully. The down-moving debris, on reaching the bottom of the vale, turned left (toward the right in the pictures) and continued in the gully for over 250 feet, ending in a small mud tongue. At the turn (Fig. 7) the right valley-side was plastered with sod balls and caked mud. The large area of this mud cover, its well-defined outer

edge, and its relatively high location on the gully wall indicate that the whole mass loosened above passed at this point as a unit. The slipout occurred on a slope of 23°. The depth of the regolith removed measured 3 feet at the most. Sandstone became exposed at different points on the scar.

Figure 8 pictures a disintegrating slip which occurred on a slope of very gentle declivity. At the scar the slope dips at an angle of 15°; at the lower end of the 200-foot train the ground slopes at an angle of 6°. Both angles represent minimum values found associated with these soil slips. The clods are relatively large, measuring a foot or more. The source depression covers an area of 25×25 feet and attains a greatest depth near the backslope of 4–5 feet. Its floor dips outward at all points. No bedrock is exposed.

The series of slips of Figure 9 moved out on a slope of 25°. The depth of regolith involved measured 2–3 feet. Exposures of the regolith in place showed the upper foot to consist of clayey soil, while the subsoil was a coarse rubble of sandstone in which soil occupied only the wide interstices. Coherent bedrock was nowhere exposed. The trains consisted of caked mud and sandstone blocks up to 8 inches in greatest dimension, with very few commingled balls of sod or soil. Numerous and well-trodden cow contours 2 and 3 feet wide did not interfere with the downward advance of the debris. The character of the regolith and the steep inclination of the slope favored thorough disintegration of the sliding mass, resulting in a greater scattering of the material and the absence of a good tongue shape.

The source depression of the slip of Figure 10 is exceptionally long compared to its width, having dimensions of 80×30 feet. The depth of soil involved in the movement was not over 2 feet. One to two weeks after the occurrence of the slip, numerous pieces of sod, the largest 4×6 feet, still lay in the depression in an upright position. Their locations and outlines clearly showed that they had slid the short distance from their original position. Sliding is thus definitely the

FIG. 6.—Sharp turn forced upon the train of a disintegrating soil slip by a slope gully. In foreground the terminal mud tongue. Pacheco Hill.

major movement in the source depression. No bedrock or rock rubble was exposed. The inclination of the slope was 22°. The three separate trains of rolled clods indicate that three separate slipouts took place side by side. The shallowness of the regolith and the steepness of the slope were again not conducive to the formation of well-outlined tongues of deposition.

ORIGIN OF DISINTEGRATING SOIL SLIPS

The relation of disintegrating soil slips to rain is quite apparent. The fresh scars are seen only during the winter rainy season and are particularly conspicuous shortly after heavy rains lasting a number of days. They are more numerous in years of very high precipitation than in years of low precipitation. The appearance of the deposits—dry mud balls and caked mud—clearly attests to lubrication by precipitation.

The mass of a slip obviously moves out as a unit. This is well substantiated by (*a*) the great distance traveled by the debris, (*b*) the common tongue shape of the deposit, (*c*) the lateral ridges in the upper half of the tongue, and (*d*) the location and configuration of the broad area of caked mud at the bend shown in Figure 7. Although the mass slips out as a unit, it appears to lose coherence very readily. This is shown by (*a*) the general scattering of the debris, particularly on steep slopes, (*b*) the absence of lateral ridges in the lower part of the tongue, and (*c*) the common rounding of the individual pieces. This quick division of the sliding mass clearly indicates that the downward movement is relatively rapid, even on quite gentle slopes. A relation of rapidity of disintegration and downward movement to slope declivity is borne out by the dominant sizes of the clods, which are larger on gentle slopes (cf. Figs. 3 and 4), and by the relative scattering of the debris, which increases with slope declivity.

FIG. 7.—Close-up of the turn of Fig. 6

Although it is very probable that small pieces of the back wall of the source depression will continue to break off after the slip takes place, no evidence was found indicating that one slip is followed soon by a slipout taking place directly above. Such succession would leave its mark in the superposition of debris trains

and in a doubling of lateral ridges on one or both sides, arrangements which were not encountered. The slipout seems to alleviate the conditions conducive to its formation. Only the lateral extension of a slipout along a contour was met (Fig. 10).

The depth of regolith involved is always small, 5 feet at the most. A clear relation to slope declivity exists, thinner layers slipping off on steeper slopes where the component of gravity parallel to the slope is greater and where the soil and weathered regolith are shallower.

Disintegrating soil slips originate, therefore, when a shallow zone of soil or regolith, not more than 5 feet in depth, has become thoroughly moistened to a point close upon saturation. When this state is reached, a limited area, seldom larger than 20×30 feet, slides out as a unit and disintegrates rapidly into its constituent parts of sod, soil, and bedrock blocks, which then roll individually downslope, the plastic masses thereby acquiring a spheroidal shape.

LUBRICATION OF REGOLITH

Thomas[3] attempted to account for the thorough lubrication by postulating that these soil slips occurred in local bedrock pockets which collected and ponded the percolating rain water. But no such bedrock pockets were found at any of the slips investigated. The numerous and deep highway cuts on Marin Peninsula reveal no bedrock pockets of requisite size. Where the boundary between bedrock and regolith is relatively sharp, the bedrock surface is rather smooth. Most common is a gradation from bedrock through rubble into the superjacent soil. Moistening to a degree conducive to sliding thus does not depend on the presence of such collecting pockets. The common gradation from bedrock into regolith makes it improbable that sliding commonly takes place along the indefinite, nay, nonexistent, boundary between bedrock and regolith. Only in one slip visited (Fig. 7) is there any probability that sliding took place on the bedrock surface. In all other slips visited the sliding surface obviously developed within the regolith itself. Sliding must thus result from the interaction of infiltration and downward percolation at depth. Where the former takes place at a rate greater than the latter, the water content of the top zone will increase to the critical point at which sliding will originate.[4]

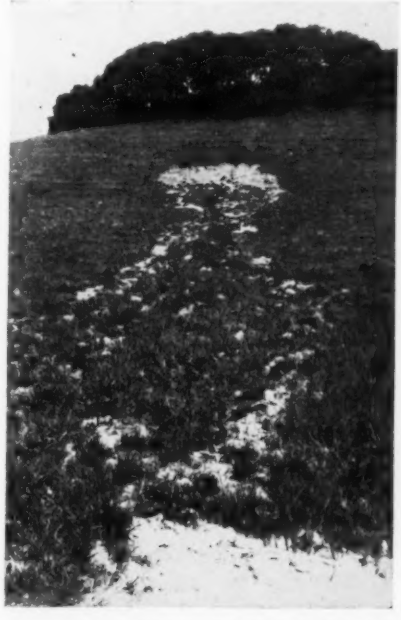

FIG. 8.—Partly overgrown train of a disintegrating soil slip that occurred on a slope of very gentle inclination. Two miles east of San Rafael on road to McNear's Point.

[3] *Op. cit.*, pp. 18, 46–47.

[4] The concept that increase in weight through infiltration of rains causes sliding has been effectively dispelled by Walther Hacker in his paper, "Overloading as a Motor of Mass-Movement," *Annals Assoc. Amer. Geog.*, Vol. XXX (1940), pp. 271–76.

FIG. 9.—Marked scattering of debris of a disintegrating soil slip caused by steepness of slope and poor coherence of regolith. Headwater of Salmon Creek, 17 miles northwest of San Rafael. The wavy surface configuration of the foreground is caused by earth flowage.

FIG. 10.—Series of disintegrating soil slips arranged along a contour. Headwater of Salmon Creek

The verity of this conclusion seems established by the occurrence of soil slips almost exclusively during periods of prolonged and heavy rains. The fact that a disintegrating soil slip is never followed by a second slip directly above, despite the increase in slope gradient produced by the slipout, appears as a further verification of this reasoning. The ease of drainage through the break-away scarp of a disintegrating soil slip obviously prevents accumulation of moisture to a stage at which sliding will be repeated. The very large proportion (50 per cent and more) of clay in the hill soils around the bay of San Francisco facilitates their saturation and accounts for their mobility, as was well shown by Thomas.

FIG. 11.—Appearance of slip shown in Fig. 3 three months later.

FIG. 12.—Appearance of slip shown in Fig. 4 three months later.

INFLUENCE OF SLOPE DECLIVITY AND VEGETATION

Disintegrating soil slips occur on all parts of a slope but are most numerous on its upper half. They were never found to start from the very crest, which is commonly convex in the coastal hills of California. The uppermost slips usually occur where the crestal convexity merges into the steepest and commonly straight section of the slope (see Figs. 9 and 10).

Disintegrating soil slips occur sometimes together with slumps and earthflows on the same slope. In this case slumping and earth flowage are characteristic of the lower part of the slope and soil slipping of its upper part (see Fig. 9). The relation of the two forms of landsliding to slope declivity is then

quite obvious, steeper slopes favoring disintegrating soil slips. Where both forms of sliding occur on the same slope, it is also quite evident that soil slipping involves a layer of regolith only a half or a third as deep as that effected by slumping and flowage.

Some slopes of medium steepness were found subject to extensive slumping and flowage and showed no signs of disintegrating soil slips, while other slopes of similar steepness displayed only scars of disintegrating soil slips and were devoid of slumps with bulging toes. The depth of the regolithic cover of fine texture appears to be the factor which determines whether disintegration and rolling of the fragments or coherence and plastic flow shall follow upon the initial sliding, a thin cover favoring disintegration, a thick cover inducing plastic flow.

Disintegrating soil slips are especially common on grassy slopes. They were not seen on slopes with a good stand of open oak forest (oak chaparral) or with dense evergreen or coniferous forest. They occur, however, quite readily on brush-covered slopes of sufficient steepness. Tree roots appear to hold the regolith better than the roots of brush or grass.

FIG. 13.—Two soil slips which probably occurred about a year apart. Near McNear Point, 3 miles east of San Rafael.

On many ridges of the Marin Peninsula the disintegrating soil slips are numerous enough to indicate that they are a noteworthy process in local degradation. Since similar features have not been described from the humid East, there is a possibility that these disintegrating soil slips are peculiar to the West The poor binding quality of the California grasses, which are shallow-rooted and form no solid sod, may account for the ease of disintegration of these small

slips. In the humid East, under similar conditions of precipitation, a slipping mass of similar size may possibly retain its coherence and form a slump or earthflow.

READY ELIMINATION OF ALL SIGNS OF SLIPPING

The mud and clod trains of the disintegrating soil slips are very ephemeral features. Figures 11 and 12 show the appearance of the soil slips pictured in Figures 3 and 4, about three months after their occurrence. Figure 13 shows a fresh slip side by side with an older slip which is judged to date back to the preceding winter of very high precipitation. Rainwash, drying and cracking, piercing by grass, and to some degree, also, trampling by cattle are held responsible for the rapid destruction of the caked mud patches and the clod balls. The lateral ridges in proximity to the slip depression withstand disintegration the longest. Later on, only the source depression remains as evidence of such a slipout. At this state the depression could readily be interpreted either as the work of man or as resulting from spring sapping. No slip was found to be associated with a spring. Numerous slips, possibly the majority, were encountered in shallow slope dales (Figs. 4 and 7), where slope-induced concentration of runoff and percolation facilitates their formation. The series of slips of Figure 4 occurred in a slope dale which showed signs of seepage in its lower part for weeks after the advent of rains. At one locality a soil slip proved a means of headward extension of a slope gully (Fig. 14).

Most source depressions of soil slips grass over quite readily. Only one old depression was encountered which had not acquired a cover of grass. Rainwash had transformed it into a miniature gully head with a main branch and two tributaries separated by clay ridges 2–3 feet high. However, no gully followed below this head. The collected runoff had not been able to carve a permanent channel on the grassy slope below.

FIG. 14.—Gully extension through a disintegrating soil slip. The vigorous gully cutting is judged to have followed upon the slipping, the bared surface increasing the runoff. In foreground and middle ground two miniature alluvial cones. Novato Valley, 12 miles north of San Rafael.

CLASSIFICATION

It is difficult to assign a proper place to these disintegrating soil slips in C. F. S. Sharpe's[5] genetic system of classification of landslides, since the combination of sliding with subsequent disintegration and rolling permits a classification under sliding and rapid flowage. If these disintegrating soil slips were many times larg-

[5] *Landslides and Related Phenomena* (New York: Columbia University Press, 1938).

er, they would qualify as debris avalanches. By Sharpe's definition of the latter,[6] the disintegrating soil slips should be termed "debris avalanches," a designation in conflict with their small size. The slips cannot qualify as debris slides in Sharpe's sense of the term,[7] since they leave no "irregular hummocky deposit" and do not take place in a relatively dry state.

If a classification in Sharpe's system of mass movements is desired, it appears that the disintegrating soil slips would have to be included in his category of debris avalanches, in which they could be treated as a subgroup characterized mainly by their small size.

[6] *Ibid.*, pp. 61, 74.

[7] *Ibid.*, p. 74.

CHINK-FACETED PEBBLES: FLUVIATILE VERSUS MARINE

CHESTER K. WENTWORTH
Board of Water Supply, Honolulu, Hawaii

ABSTRACT

Chink-faceted pebbles were first identified as due to restricted abrasion of smaller pebbles and rock fragments between the larger and more stable boulders of coarse beach deposits. Similar pebbles were later found in stream channels in special situations where restricted mutual rubbing was favored. Further observations show that they occur sparingly in certain places in the steeper parts of many rocky channels in Hawaii. Most interesting and specialized is the occurrence of such pebbles in small groups in potholes and crevices in the faces of waterfalls, where they are continuously agitated by the normal low-water flow that falls close to the rock face. Here they suffer effective restricted abrasion but are protected against being wholly dislodged during floods, since the floodwater is thrown farther out from the rock and passes clear of the crevices in which the pebbles are lodged. Fluviatile chink-faceted pebbles are probably more irregular and less rounded in general shape than are those of marine origin.

INTRODUCTION

Chink-faceted pebbles were first described in 1925. The pebbles then under discussion were of marine origin, and after analysis of the conditions of their formation it was concluded that these are much more likely to occur on beaches than in stream channels, though it was conceded that the latter occurrence was a possibility.[1] In 1936, after the writer had traversed many miles of inland stream channels in connection with ground-water studies, a note was published on the existence of fluviatile chink-faceted pebbles.[2] The present paper is based on six more years of water-supply studies which have afforded occasional opportunities to examine fluviatile chink-faceted pebbles and their situs of origin. Since such pebbles cannot by any means be called abundant and since they occur in rugged, mountainous country where much of the channel-traversing is done by rope, their study is necessarily a by-product of long-continued areal studies.

[1] Chester K. Wentworth, "Chink-faceting: A New Process of Pebble-shaping," *Jour. Geol.*, Vol. XXXIII (1925), pp. 260–67.

[2] "A Note on Chink-faceted Pebbles (Hawaii)," *Jour. Geol.*, Vol. XLIV (1936), p. 645.

THE CONDITIONS OF CHINK-FACETING

In the original description of the process of chink-faceting, the subject was treated under four headings, the essential part of each being quoted at the head of the following paragraphs.[3]

These specifications were written when marine chink-faceted pebbles only were known. It is interesting and furnishes an instructive point of departure (now that fluviatile chink-faceted pebbles have also been found) to consider to what extent these earlier specifications are applicable. The comparison will be facilitated by considering the four paragraphs in the same order.

1. "A stable fabric of coarse material, with a relatively small amount of fine material. Coarse stream gravel deposits are more commonly covered or choked by finer deposits." This condition is approximated in the stream-channel sites, with some differences from the beach conditions. Many stream channels carry lodged boulders of very large size—up to several feet in diameter. It appears, however, that in stream channels the large boulders are less well sorted, less abraded,

[3] "Chink-faceting . . . . ," *op. cit.*, p. 267.

and are more generally surrounded by close-packed smaller detritus. In the beach structure the pebbles showing chink-faceting are more generally surrounded and locked against removal even from above than in the stream channel. In the stream channel the chink-faceted pebbles are found in small groups, either in interstices between large boulders or in small crevices or ill-formed potholes in the bedrock of lava flows. They are not found in any general, extensive gravel deposit where the cobbles are well sorted as to size.

2. "An intermittent to-and-fro movement of the water. Stream flow is in the same direction at all times and is relatively steady." This requirement could have been better worded as "an intermittent movement causing recurrent to-and-fro movement of the pebble." The movement of the water may or may not be to-and-fro, since successive water impulses, combined with gravity, may produce the same effect. This condition seems to be the common one in stream-channel, chink-faceting situations. The most common place of chink-faceting is at the foot of waterfalls, where the water falls on clusters of pebbles that are not under deep water. The falls may be over rock cliffs or may be mere rills coming over the clefts between large boulders, as will be elaborated later.

3. "A dashing, swashing, upward movement of the water into a previously unsaturated part of the beach structure. Stream flow is mostly downward and mostly into continuously saturated masses of gravel or other sediment." While in a general way this is true of streams, the writer in 1925 failed to allow for the pulsatory action of small waterfalls and other parts of small, rock-filled channels. Anyone can verify that the flow of water in steep, rocky channels is indeed pulsatory and turbulent and also that, owing to this action or even to effect of wind, the impact of the water at the foot of a small fall at any particular place is far from continuous and steady. These variations, combined with gravity, make effective conditions for chink-faceting.

4. "Constancy of conditions at a given place over long periods of time. Stream regimen is subject to frequent and great fluctuations. Return annually or more frequently to a given set of conditions is conceivable but is in general unlikely." The most important factor in the formation of fluviatile chink-facet pebbles appears to lie in a mechanism which operates to make the work of a recurrent favorable set of conditions cumulative, while protecting the chink-facet fabric of pebbles from derangement by intervening unfavorable conditions. This is best shown in the cluster of pebbles, in process of chink-faceting, which lies close to the cliff of a waterfall, preferably in a pothole or crevice above the bottom or the water surface of the plunge pool even in flood time (Fig. 1). The process of chink-faceting is active when just sufficient water is flowing to send a small fall or jet of water to agitate but not derange the cluster of pebbles. When in flood time there is a material increase of water in the channel, the larger fall is thrown farther out and may miss the crevice altogether, or the small amount may continue. In any event, repeated observation of chink-faceting in such places indicates that they are rather effectively protected from derangement of pebbles by flood water and, because of the fixed form of the rock channel above, are assured of recurrent action in a rather precise repetition of pattern (Fig. 1).

To a lesser extent, chink-facet clusters which lie in channel-bottom sites where they receive a trickle from over one or

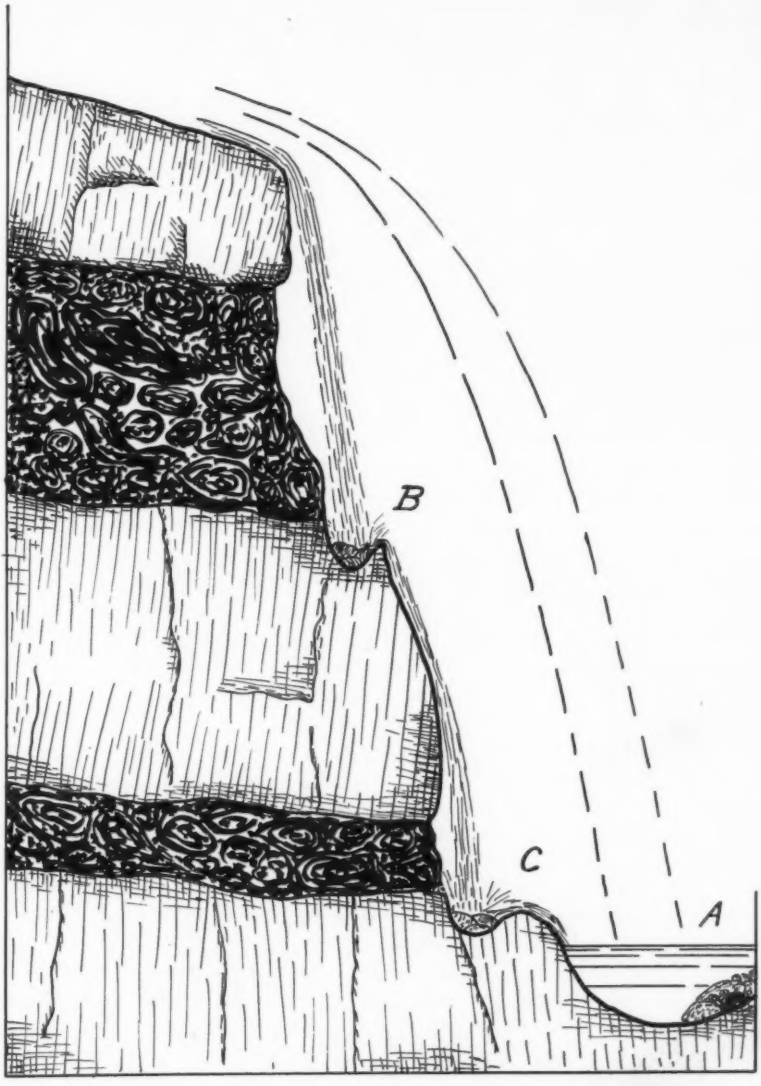

FIG. 1.—Sketch of waterfall, showing chink-facet pebble sites and course of water during normal and flood times. Very few Hawaiian waterfalls fall clear and vertical below a dominant ledge for more than 10 or 15 feet, and the profile is one showing an over-all angle of 60°–80°, which affords some foothold by which many hundreds, 10–200 feet in total height, have been traversed by rope in the course of the present survey. The result is that the main plunge pool (*A*) at the base is developed in relation to the clear leap of the more effective flood flows, but during most of the time the smaller, more usual flow alternately trickles and falls with more continuous contact with the rock. Pebbles of a suitable size and shape to remain in small crevices and potholes (*B* and *C*) are caught by accident and remain, subject to agitation below the intensity which would throw them out but immune from the flood action following heavy rains.

more boulders in low-water times may be safe from disturbance when water flows one or several feet deep over them in short flood periods. It should be noted that the stream channels in question are channels in which flood conditions may prevail for a few hours but which are not drastically modified with great frequency. In so far as the chink-facet localities are in gravel-filled sections, they are in sections either very close to bedrock outcrops or dominated by large, partly buried boulders.

SHAPES OF FLUVIATILE CHINK-FACETED PEBBLES

The occurrence of both marine and fluviatile chink-faceted pebbles is so sporadic that any valid statistical comparison of their shapes does not seem practical. In general, it appears that well-rounded forms, with distinct, sharply limited facets imposed on the rounded form, are more abundant in marine than in fluviatile situations and that elongated curved, or more grotesque shapes, largely bounded by facets, are more commonly found in fluviatile sites. The marine sites are on coasts subject to strong wave attack, and the smaller cobbles locked between larger boulders or the ledge rock are often well rounded and consist of hard, unweathered rock. The gravel in streams, though containing many large boulders well rounded by weathering, is much less effectively abraded and is, in general, much softer and more weathered rock. Because of this greater softness, the more irregular and variable shape, and the fact that the fluviatile chink-faceted cobbles are not locked against removal from above, they seem more commonly to lie bedded in mutually interfitted groups, where more completely chink-faceted shapes are developed.

In marine chink-faceted cobbles, single, isolated unit facets seem more common; in the fluviatile type many facets are complex and progressive, suggesting a slow skidding into position, perhaps in relation to the shifting or wear of other pebbles rather than through control by an unyielding pattern of large adjacent boulders. On many such pebbles no two persons would agree in a count of the number of facets, though all would recognize that a large number were present.

Naturally, many chink-faceted pebbles, especially the larger ones, have only a few fresh facets marking a small part of the surface and standing out distinctly on it. Or a part of the background surface may consist of more obscure older facets which have acquired the standard texture and color of the main surface. The surface of others may consist largely of simple and complex facets or else of areas which show the characteristic rubbing but which would hardly be called "facets" (Figs. 2, 3, 4). Some facets are distinguished only by the texture; others may be sharply cut, deeply grooved, or indented, according to the shape of the opposing pebble and the intensity of the action. Some facets cut cleanly across vesicles or fissures in the surface without deviation; others are deepened or controlled in the vicinity of such depressions. Despite all this variation, seemingly more marked or more general than in the marine type, the fluviatile chink-faceted pebble or cobble remains a distinct type which is clearly distinguishable from ordinary stream pebbles and denotes a distinctive habitat.

SUMMARY

Chink-faceted pebbles, cobbles, or boulders are those which have been subject to a limited, recurrent rubbing against a limited portion of another rock fragment or ledge of bedrock so as to produce a smoothed, distinct, and often sharply limited facet. Most commonly,

FIG. 2.—Chink-faceted pebble about 3 inches long, showing one side with numerous facets grading into one another. The pebble is marked in this fashion over nearly its whole surface.

FIG. 3.—Pebble showing multiple-chink facet with its components partly controlled by olivine crystals, which are harder than the matrix and form salients protecting the matrix in the lee.

such fragments, because of the very restriction which insures repetition of the same rubbing, have several facets which have been simultaneously acquired. Not uncommonly, such pebbles have been successively faceted and rearranged so as to that by which grass stems, tree branches, and the like make controlled grooves and rubbing marks on sand, soil banks, or soft rock, even wind might so move a small pebble as to produce such marks. A close parallel is the curious, recurrently

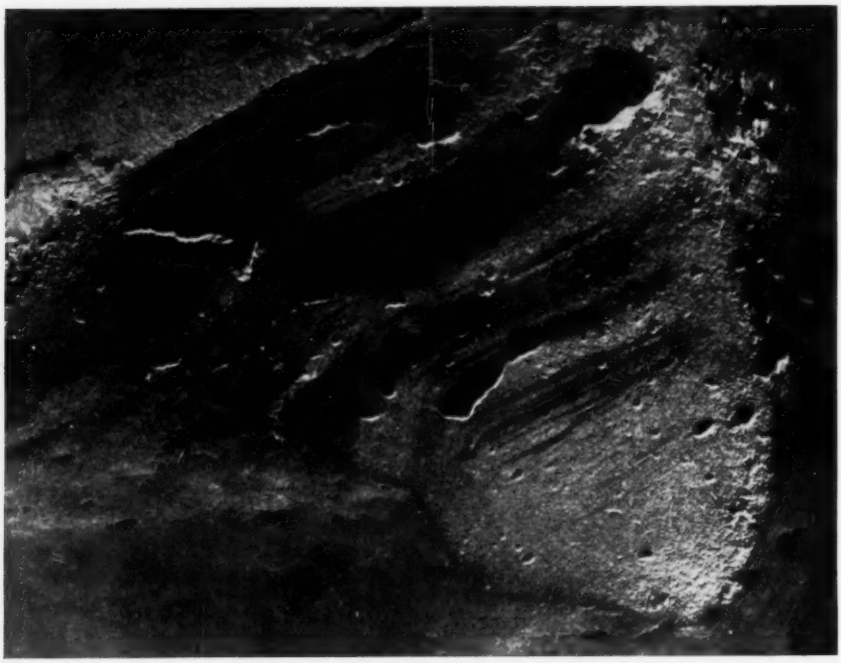

FIG. 4.—Detail of 1-inch facet showing grooved configuration resulting from motion fixed in parallel directions but with considerable lateral freedom and perhaps multiple contact on other pebbles.

to be rather generally marked if not largely shaped by this process.

Chink-faceting depends on some combination of restraint or stability plus controlled and recurrent impulses from water. Though beach conditions seem more likely to produce them than stream conditions, observations in Hawaii show that they may be produced in either and that in stream sites they may be the product of more particularized conditions than on beaches. It is probable that similar pebbles may be produced by other agents; since the process is not unrelated drilled nubbin that sometimes is recovered with the core or from the casing of a core-drilling operation.

Until many more observations have been made, and by different observers in various regions, it is scarcely justified that anyone make interpretations as specific as the writer made in 1925. To what extent the formation of such pebbles is favored by the general toughness and lack of individual, hard mineral grains which characterize basalt is one of the questions which must await more general observations in regions where other rocks occur.

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